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System and method for autonomously removing fasteners embedded in wood products

Abstract

A method includes: receiving a recycled wood workpiece populated with a set of metal fasteners; accessing an internal imaging scan; detecting the set of metal fasteners embedded in the recycled wood workpiece based on internal features detected in the internal imaging scan; for each metal fastener in the set of metal fasteners, extracting an initial position and an initial orientation of the metal fastener from the internal imaging scan; generating a virtual model of the recycled wood workpiece based on the internal imaging scan; accessing an image captured by an optical sensor; detecting a first metal fastener in the recycled wood workpiece; deriving a first position and a first orientation of the first metal fastener; and, in response to identifying the first metal fastener analogous to an initial metal fastener in the virtual model, isolating the first metal fastener in the virtual model and generating a fastener removal schedule.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application claims the benefit of U.S. Provisional Application No. 63/316,933, filed on 4 Mar. 2022, 63/316,935, filed on 4 Mar. 2022, and 63/419,244, filed on 25 Oct. 2022, each of which is incorporated in its entirety by this reference.

TECHNICAL FIELD
(1) This invention relates generally to the field of material recycling and more specifically to a new and useful system for autonomously removing fasteners embedded in wood products in the field of material recycling.

Description

BRIEF DESCRIPTION OF THE FIGURES
(1) FIG. **1** is a schematic representation of a system;
(2) FIG. **2** is a flowchart representation of a method;
(3) FIGS. **3**A and **3**B are schematic representations of one variation of the system;
(4) FIGS. **4**A and **4**B are schematic representations of one variation of the system;
(5) FIG. **5** is a flowchart representation of one variation of the method;
(6) FIGS. **6**A and **6**B are schematic representations of one variation of the system;

(7) FIGS. **7**A and **7**B are schematic representations of one variation of the system; and

(8) FIGS. **8**A and **8**B are flowchart representations of one variation of the method.

DESCRIPTION OF THE EMBODIMENTS

(9) The following description of embodiments of the invention is not intended to limit the invention to these embodiments but rather to enable a person skilled in the art to make and use this invention. Variations, configurations, implementations, example implementations, and examples described herein are optional and are not exclusive to the variations, configurations, implementations, example implementations, and examples they describe. The invention described herein can include any and all permutations of these variations, configurations, implementations, example implementations, and examples.

(10) 1. System

(11) As shown in FIGS. **1**, **3**A, **3**B, **4**A, **4**B, **6**A, **6**B, **7**A, and **7**B, a system **100** for autonomously removing fasteners embedded in a recycled wood workpiece **115** includes: an X-ray scan module **112**; a chassis **102**; a conveyor **105**; an optical sensor **110** (e.g., 3D depth camera); a fastener extractor module (e.g., a non-threaded fastener extractor module **120**, a threaded fastener extractor module **130**); a metal scan module **150**; and a primary controller **160**.

(12) The chassis **102** defines a scan volume and a work volume **109**. The conveyor **105** runs from an entry of the chassis **102** to an exit of the chassis **102** and is configured to receive a recycled wood workpiece **115** populated with metal fasteners. The X-ray scan module **112** is supported by and arranged within a threshold distance of the entry of the chassis **102** and includes an X-ray sensor facing the scan volume. The optical sensor **110** faces the work volume **109**.

(13) The fastener extractor module includes: a stage supported by the chassis **102**; an extractor end effector supported and manipulated on the chassis **102** via the stage and configured to engage and retain metal fasteners from a section of the recycled wood workpiece **115** occupying the work volume **109**; and a controller (e.g., local controller **170**). The controller (e.g., local controller **170**) is configured to: access a series of X-ray scans of the recycled wood workpiece **115** within the scan volume captured by the X-ray sensor; compile the series of X-ray scans into a virtual model of the recycled wood workpiece **115** annotated with positions, orientations, and fastener types of metal fasteners extracted from the series of X-ray scans; and access an image of the work volume **109** captured by the optical sensor **110**. Based on features detected in the image, the controller (e.g., local controller **170**) is further configured to detect a first metal fastener in the section of the recycled wood workpiece **115** occupying the work volume **109** and extract a position and orientation of the first metal fastener. The controller (e.g., local controller **170**) is also configured to: map the first metal fastener in the section of the recycled wood workpiece **115** to the virtual model based on the position and orientation of the first metal fastener; and prescribe a fastener removal schedule defining a tool path for the extractor end effector to extract the first metal fastener from the section of the recycled wood workpiece **115**.

(14) The metal scan module **150** is arranged on the chassis **102** within the threshold distance of the exit of the chassis **102** and includes a metal line scanner facing the scan volume and configured to detect metal fasteners within the recycled wood workpiece **115**. The controller is further configured to: access a first metal scan of the recycled wood workpiece **115** within the scan volume, captured by the metal line scanner; trigger the conveyor **105** to drive the recycled wood workpiece **115** to a recycled wood workpiece **115** pallet; and reset the conveyor **105** to an initial position at the entry of the chassis **102**, in response to absence of metal fasteners detected in the first metal scan of the recycled wood workpiece **115**.

(15) One variation of the system **100** includes: a chassis **102** defining a work volume **109**; a conveyor **105** configured to receive the recycled wood workpiece populated with metal fasteners and configured to constrain a section of the recycled wood workpiece **115** within the work volume **109**; an optical sensor **110** facing the work volume **109**; a non-threaded fastener extractor module; and a controller (e.g., local controller **170**). The non-threaded fastener extractor module **120**

includes a stage **121** supported by the chassis **102** and a non-threaded fastener end effector **122**. The non-threaded fastener end effector **122** is supported and manipulated on the chassis **102** via the stage **121** and includes: a set of jaws **128** configured to engage and retain metal fasteners from the section of the recycled wood workpiece **115**; and a jaw actuator **125** configured to actuate the set of jaws **128**. The controller is configured to: access an image of the work volume **109** captured by the optical sensor **110**; based on a set of features detected in the image, detect a first fastener in the section of the recycled wood workpiece **115** occupying the work volume **109** and derive a first position and a first orientation of the first fastener in the work volume **109**; define a first target engagement position of the non-threaded fastener end effector **122**, to engage the first fastener, based on the first position and the first orientation of the first fastener within the work volume **109**; trigger the stage to drive the non-threaded fastener end effector **122** to the first target engagement position; trigger the jaw actuator **125** to drive the set of jaws **128** to engage the first fastener in the section of the recycled wood workpiece **115**; and trigger the stage **121** to retract the non-threaded fastener end effector **122** from the first target engagement position to extract the first fastener from the recycled wood workpiece **115**.

(16) 2. Applications

(17) Generally, the system **100** is configured to recycle used lumber (e.g., construction wood products) populated with metallic objects by: receiving an inbound recycled wood workpiece **115**; scanning the inbound recycled wood workpiece **115** with a set of internal imaging, depth, and/or color sensors; implementing computer vision techniques to detect and distinguish threaded fasteners (e.g., screws) and non-threaded fasteners (e.g., straight nails, bent nails, staples) in the recycled wood workpiece **115**; and then selectively manipulating a set of threaded fastener and non-threaded fastener extractor modules **120** to autonomously engage, retain, and remove these fasteners.

(18) For example, the system **100** can process recycled wood workpieces **115** (e.g., wood products) including recycled wood workpieces **115**, joists, beams, columns, and plywood sheet goods to: characterize recyclability qualities of sections of these wood products; mark or resect sections of these wood products for discard based on embedded metal, structural damage, or low recyclability quality within these sections; and detect and remove threaded fasteners (e.g., screws), non-threaded fasteners (e.g., straight nails, bent nails, staples, retainer nails), and other metallic objects embedded and/or extending above the sections of these recycled wood workpieces **115** characterized by sufficient recyclability qualities.

(19) Furthermore, the system **100** can receive a recycled wood workpiece in a scan volume of an X-ray scan module. Then the primary controller **160** can: access internal imaging data captured by the X-ray scan module **112**; detect internal features representing metallic objects (e.g., possible metal fasteners) in these internal imaging data; extract positions orientations of these internal features; identify a fastener type of each internal feature; and compile these internal imaging data into a three-dimensional representation (or "virtual model") of the recycled wood workpiece **115** annotated with positions, orientations, and fastener types (e.g., non-threaded, threaded, nail, staple, screw). The system **100** can then receive a recycled wood workpiece **115** in a work volume **109** of a fastener extractor module (e.g., non-threaded fastener extractor module **120**, threaded fastener extractor module **130**). The primary controller **160** can then: access optical scan data captured by an optical sensor **110** and/or set of optical sensors **110** facing the work volume **109**; detect external features embedded within and/or extending above surfaces of the recycled wood workpiece **115** based on these optical scan data; map each external feature to a corresponding internal feature in the virtual model; identify each external feature and internal feature pair as a metal fastener; generate a fastener removal schedule to remove each fastener from the recycled wood workpiece **115**; and transmit each fastener removal schedule to a local controller **170** of a corresponding fastener extractor module (e.g., non-threaded fastener extractor module **120**, threaded fastener extractor module **130**) to execute each fastener removal cycle.

(20) 2.1 Non-Threaded Fastener Extractor Module

(21) Furthermore, the system **100** can also include a set of non-threaded fastener extractor modules **120**. Each non-threaded fastener extractor module **120** includes: a stage (e.g., multi-axis stage); a non-threaded fastener end effector **122**; a set of module actuators; and a local controller **170**. The non-threaded fastener end effector **122** includes: a bearing plate **123**; a vertical stage **124** arranged on the multi-axis stage **121** and is configured to support the bearing plate **123**, advance the bearing plate **123** toward a non-threaded fastener in a recycled wood workpiece **115** occupying the work volume **109**, and retract the bearing plate **123** to withdraw the non-threaded fastener from the recycled wood workpiece **115**; and a jaw actuator **125** arranged on the vertical stage **124**, coupled to a set of jaws **128** and configured to close the set of jaws **128** to engage the set of jaws **128** against a non-threaded fastener and to open the set of jaws **128** to release the non-threaded fastener from the set of jaws **128**.

(22) The system **100** can execute a non-threaded fastener removal cycle in conjunction with each non-threaded fastener extractor module **120**. For example, the primary controller **160** can further characterize a quality of the recycled wood workpiece **115** based on internal features within the virtual model and identify each non-threaded fastener as a nail and/or a staple (e.g., straight nail, bent nail) and a characteristic of the nail and/or staple (e.g., superficial, subsurface, flush, normal, non-normal relative a surface of the recycled wood workpiece **115**, dimension). The local controller **170** can then execute a non-threaded fastener removal schedule by: autonomously navigating the non-threaded fastener end effector **122** to a target engagement position, via the stage **121** (e.g., multi-axis stage), and to a target jaw position, via the yaw actuator **127** above the nail and/or staple in the recycled wood workpiece **115**; and trigger the jaw actuator **125** to close the set of jaws **128** to engage the set of jaws **128** against the nail and/or staple with a target clamping force. Upon completion of the non-threaded fastener removal cycle, the local controller **170** can trigger the vertical stage **124** to retract the bearing plate **123** to extract the nail and/or staple from the recycled wood workpiece **115** and trigger the jaw actuator **125** to open the set of jaws **128** to release the non-threaded fastener from the set of jaws **128** into a fastener container **145** (e.g., waste bin).

(23) The local controller **170** can then verify removal of the non-threaded fastener from the recycled wood workpiece **115**. If the non-threaded fastener crosses a beam sensor in the fastener container **145**, the local controller **170** can confirm removal of the non-threaded fastener at the end of the non-threaded fastener removal cycle. If the non-threaded fastener does not cross the beam sensor in the fastener container **145**, the local controller **170** can flag the non-threaded fastener as a failure at the end of the non-threaded fastener removal cycle. Alternatively, if the offset distance of the set of jaws **128** falls below an offset distance threshold, the local controller **170** can flag the non-threaded fastener as a failure at the end of the non-threaded fastener removal cycle.

(24) Additionally, the system **100** can implement computer vision techniques to detect and distinguish removal failures (e.g., slipped, snipped, broken, missed) for non-threaded fasteners. The system **100** can then update a fastener removal schedule to reduce failure of future fasteners with analogous characteristics such as fastener type, location relative the recycled wood workpiece **115** (e.g., subsurface, superficial, flush, normal, non-normal relative the surface of the recycled wood workpiece **115**), and/or fastener size.

(25) 2.2 Threaded Fastener Extractor Module

(26) The system **100** can also include a set of threaded fastener extractor modules **130**. Each threaded fastener extractor module **130** includes: a stage **131** (e.g., a multi-axis stage); threaded fastener end effector **132**; a set of module actuators; and a local controller **170**. The multi-axis stage is arranged in a work volume **109** defined by the chassis **102** and faces the work volume **109**. The threaded fastener end effector **132** is supported by the multi-axis stage and includes: a housing **134**; a ram **136** arranged and configured to rotate in the housing **134**; a set of jaws arranged on a distal end of the ram **136**; a jaw actuator configured to close the set of jaws against the threaded fastener; and a ram actuator **137** (e.g., drive motor) configured to rotate the ram **136** on the housing **134**. The

set of module actuators is configured to manipulate the multi-axis stage **131**. The local controller **170** is configured to selectively actuate the set of module actuators, the jaw actuator **138**, and the ram actuator **137** to engage and remove the threaded fastener from the recycled wood workpiece **115** based on the fastener removal schedule.

(27) Furthermore, the system **100** can execute a threaded fastener removal cycle in conjunction with the threaded fastener extractor module **130**. For example, the primary controller **160** can further characterize a quality of the recycled wood workpiece **115** based on internal features within the virtual model and identify each threaded fastener as a screw and a characteristic of the screw (e.g., superficial, subsurface, flush, normal, non-normal relative a surface of the recycled wood workpiece **115**, dimension). The local controller **170** can then execute a threaded fastener removal schedule by: autonomously navigating the threaded fastener end effector **132** to a target engagement position, via the stage **131** (e.g., multi-axis stage), and to a target jaw position, via the ram actuator **137** above the screw in the recycled wood workpiece **115**; trigger the jaw actuator **138** to close the set of jaws **139** to engage the set of jaws **139** against the screw with a target retraction force; and trigger the ram actuator **137** to rotate the ram and the set of jaws **139** to retract the screw from the recycled wood workpiece **115**. Upon completion of the threaded fastener removal cycle, the local controller **170** can trigger the stage to retract the threaded fastener end effector **132** from the target engagement position and trigger the jaw actuator **138** to open the set of jaws **139** to release the threaded fastener from the set of jaws **139** into a fastener container **145** (e.g., waste bin).

(28) The system **100** is described herein as processing recycled wood workpieces **115** (e.g., linear construction timber), such as dimension or non-dimensional 2×4 or 2×6 recycled wood workpieces **115**. However, the system **100** can additionally or alternatively process recycled wood workpieces **115** such as: joists; rafters; wood I-beams; posts, headers; laminated timber; finger-jointed timber; plywood sheet; oriented strandboard sheet; and/or MDF sheet; etc.

(29) 3. Method

(30) As shown in FIGS. **2**, **5**, **8**A, and **8**B, a method S**100** for removing fasteners from a recycled wood workpiece includes: receiving a recycled wood workpiece in a scan volume in Block Silo; accessing a first set of X-ray scans captured by an X-ray sensor facing the scan volume occupied by the recycled wood workpiece in Block S**112**; detecting a set of internal features representing metallic objects in the first set of X-ray scans in Block S**1114**; compiling the first set of X-ray scans into a virtual model of the recycled wood workpiece, the virtual model annotated with the set of internal features in Block S**120**; receiving a section of the recycled wood workpiece in a work volume of a fastener extractor module in Block S**130**; accessing a first image captured by an optical sensor facing the work volume in Block S**132**; detecting an external feature extending above the section of the recycled wood workpiece in the first image in Block S**134**; and scanning the virtual model for a first internal feature, in the set of internal features, analogous to the external feature of the section of the recycled wood workpiece in Block S**136**. The method S**100** further includes, in response to identifying the first internal feature, in the set of internal features, analogous to the external feature of the section of the recycled wood workpiece in the virtual model: identifying the external feature as a first metal fastener embedded in the section of the recycled wood workpiece in Block S**140**; deriving a first position and a first orientation of the first metal fastener from the virtual model in Block S**142**; defining a target engagement position for an extractor end effector, associated with the fastener extractor module, to engage the first metal fastener embedded in the section of the recycled wood workpiece based on the first position and the first orientation of the first metal fastener in Block S**144**; and generating a fastener removal schedule for the extractor end effector to remove the first metal fastener from the section of the recycled wood workpiece at the first target engagement position in Block S**150**.

(31) One variation of the method S**100** includes: receiving a recycled wood workpiece populated with a set of metal fasteners in Block S**110**; accessing a first X-ray scan captured by an X-ray sensor facing the recycled wood workpiece in Block S**112**; detecting the set of metal fasteners

embedded in the recycled wood workpiece based on internal features detected in the first X-ray scan in Block S**114**; for each metal fastener in the set of metal fasteners, extracting an initial position of the metal fastener from the first X-ray scan and extracting an initial orientation of the metal fastener from the first X-ray scan in Block S**116**; compiling the first X-ray scan into a virtual model of the recycled wood workpiece, the virtual model annotated with initial positions and initial orientations of the set of metal fasteners in Block S**120**; accessing a first image captured by an optical sensor facing the recycled wood workpiece in Block S**132**; and, based on features detected in the first image, detecting a first metal fastener in the recycled wood workpiece occupying the work volume and deriving a first position and a first orientation of the first metal fastener in Block S**142**. This variation of the method S**100** further includes, in response to identifying an initial metal fastener, in the set of metal fasteners, analogous to the first metal fastener in the virtual model: isolating the first metal fastener in the virtual model in Block S**136**; and generating a fastener removal schedule defining a tool path for an extractor end effector to extract the first metal fastener from the recycled wood workpiece based on the first position and the first orientation of the first metal fastener stored in the virtual model in Block S**150**.

(32) 3.1 Non-threaded Fastener End Effector

(33) As shown in FIG. **8**A, one variation of the method S**100** includes: receiving a section of the recycled wood workpiece in a work volume in Block S**130**; accessing an image of the work volume, the image recorded by an optical sensor facing the work volume in Block S**132**; extracting a set of features representing the section of the recycled wood workpiece from the image; based on the set of features, detecting a fastener embedded in the section of the recycled wood workpiece and extracting a first position and a first orientation of a head of the fastener in Block S**134**; deriving a first target engagement position of a non-threaded fastener end effector, to engage the fastener, based on the first position of the head of the fastener in Block S**144**; and deriving a first target jaw position to align a retraction axis of a set of jaws orthogonal to a longitudinal axis of the recycled wood workpiece based on the orientation of the head of the fastener in Block S**146**. This variation of the method S**100** further includes, in response to driving the non-threaded fastener end effector to the first target engagement position: rotating the set of jaws to the first target jaw position in Block S**152**; locating the set of jaws within a threshold distance of the section of the recycled wood workpiece spanning the head of the fastener in Block S**154**; triggering a jaw actuator to drive the set of jaws into the section of the recycled wood workpiece and close the set of jaws to engage the fastener in Block S**156**; and retracting the non-threaded fastener end effector to extract the fastener from the section of the recycled wood workpiece in Block S**158**.

(34) 3.2 Threaded Fastener End Effector

(35) As shown in FIG. **8**A, one variation of the method S**100** includes: receiving a section of the recycled wood workpiece in a work volume in Block S**130**; accessing an image of the work volume, the image recorded by an optical sensor facing the work volume in Block S**132**; extracting a set of features representing the section of the recycled wood workpiece from the image; based on the set of features, detecting a fastener embedded in the section of the recycled wood workpiece and extracting a position and an orientation of a shank of the fastener in Block S**134**; and deriving a first target engagement position of a threaded fastener end effector, to engage the fastener, based on the position of the shank of the fastener in Block S**144**. This variation of the method S**100** includes, in response to driving the threaded fastener end effector to the first target engagement position: locating the set of jaws within a threshold distance of the section of the recycled wood workpiece and spanning the shank of the fastener in Block S**154**; driving the threaded fastener end effector to locate a rotational axis of the threaded fastener end effector coaxial with the orientation of the shank of the fastener; triggering a jaw actuator to drive the set of jaws into the section of the recycled wood workpiece and close the set of jaws to engage the shank of the fastener in Block S**156**; and triggering a ram actuator to rotate the ram and the set of jaws about the rotational axis of the threaded fastener end effector to retract the first fastener from the section of the recycled wood

workpiece in Block S**160**.

(36) 4. System

(37) As described above, the system **100** includes: an X-ray scan module **112**; a chassis **102**; a conveyor **105**; an optical sensor **110** (e.g., a 3D depth camera, a structured light camera configured to output RGB-D depth maps and point clouds, a two-dimensional color or hyperspectral camera, a stereoscopic color camera; a thermographic camera); a fastener extractor module (e.g., a non-threaded fastener extractor module **120**, a threaded fastener extractor module **130**); a metal scan module **150**; and a primary controller **160**.

(38) 4.1 X-Ray Scan Module

(39) The X-ray scan module **112** is configured to capture a sequence of internal imaging data of the recycled wood workpiece **115** as a machine (e.g., a forklift) or a human operator drives the recycled wood workpiece **115** past the X-ray scan module **112** during a first segment of the processing cycle. Furthermore, the X-ray scan module **112** is arranged within a threshold distance of the entry of the chassis **102** of a first fastener extractor module in a set of fastener extractor modules (e.g., a set of non-threaded fastener extractor modules **120**, a set of threaded fastener extractor modules **130**) and defines a scan volume.

(40) In one implementation, the X-ray scan module **112** includes a three-dimensional X-ray sensor facing a scan volume occupied by the recycled wood workpiece **115**. In this implementation, the X-ray sensor can capture a set of X-ray scans of the recycled wood workpiece **115** as the machine (e.g., a forklift) or the human operator drives the recycled wood workpiece **115** past the X-ray scan module **112**. The primary controller **160** can then compile this set of X-ray scans into a three-dimensional model (or "virtual model")—annotated with the internal features and defining a recycled wood workpiece **115** coordinate system—of the recycled wood workpiece **115**.

(41) In one variation, the X-ray scan module **112** includes a set of three-dimensional internal imaging sensors (e.g., magnetic resonance sensors, millimeter wave sensors, X-ray sensors) facing the scan volume occupied by the recycled wood workpiece **115**. In this variation, each internal imaging sensor in the set of internal imaging sensors can capture a set of internal imaging scans of the recycled wood workpiece **115** as the machine (e.g., a forklift) or the human operator drives the recycled wood workpiece **115** past the X-ray scan module **112**. The primary controller **160** can then implement methods and techniques described above to compile these sets of internal imaging scans into a virtual model—annotated with the internal features—of the recycled wood workpiece **115**.

(42) In another implementation, the X-ray scan module **112** includes a one-dimensional X-ray line scanner arranged over (or facing laterally across) the scan volume occupied by the recycled wood workpiece **115**. In this implementation, the X-ray scanner can capture a series of X-ray line scans of the recycled wood workpiece **115** as the machine (e.g., a forklift) or the human operator drives the recycled wood workpiece **115** past the X-ray scan module **112**. The primary controller **160** can then compile these X-ray line scans into a two-dimensional X-ray scan of the recycled wood workpiece **115**.

(43) 4.2 Chassis

(44) The chassis **102**: defines a work volume **109** and includes an exo-structure arranged about each non-threaded fastener extractor module **120** and/or each threaded fastener extractor module **130**. The exo-structure is configured to: support the stage and the extractor end effector of a non-threaded fastener extractor module **120** and/or a threaded fastener extractor module **130**.

(45) In one variation, the chassis **102** includes: a first set of lateral clamps **103** to constrain lateral sides of the recycled wood workpiece **115** at an input side (e.g., entry) of the chassis **102**; a first set of vertical clamps **104** to constrain vertical sides of the recycled wood workpiece **115** at the input side of the chassis **102**; a second set of lateral clamps **103** to constrain lateral sides of the recycled wood workpiece **115** at an output side (e.g., exit) of the chassis **102**; and a second set of vertical clamps **104** to constrain vertical sides of the recycled wood workpiece **115** at the output side of the chassis **102**.

(46) 4.3 Conveyor

(47) The conveyor **105** is configured to receive the recycled wood workpiece **115** populated with metal fasteners and is configured to constrain a section of the recycled wood workpiece **115** within the work volume **109** of a fastener extractor module. The conveyor **105** also includes a set of (e.g., two) rollers arranged on each side of a longitudinal axis of the system **100** and cooperate to engage and position a recycled wood workpiece **115** along the longitudinal axis of the system **100**.

(48) In one implementation the conveyor **105** includes: an input roller **106** coupled to an input side of a lateral axis of the threaded fastener extractor module; a first set of standoffs **108** extending radially from the input roller **106**, defining a length greater than a nominal fastener length, and configured to locate the recycled wood workpiece **115** at the input side; and an output roller **107** coupled to an output side of the lateral axis of the threaded fastener extractor module and includes a second set of standoffs **108** extending radially from the output roller **107**, defining the length greater than the nominal fastener length, and configured to locate the recycled wood workpiece **115** at the output side.

(49) In one variation, the first set of standoffs **108** extend radially from the input roller **106** and exhibit triangular cross-sections with vertices offset from the input roller **106**. The second set of standoffs **108** also extend radially from the output roller **107** and exhibit triangular cross-sections with vertices offset from the output roller **107**. Accordingly, the first set of standoffs **108** and the second set of standoffs **108** cooperate to locate an adjacent recycled wood workpiece **115** between the input roller **106** and the output roller **107** during the processing and the fastener removal cycles.

(50) Additionally, the conveyor **105** includes: a set of (e.g., two, three, four) adjustable clamps configured to receive and retain the recycled wood workpiece. For example, the conveyor **105** can include: a set of lateral clamps **103** to constrain lateral sides of the recycled wood workpiece **115** at the input side of the chassis **102**; and a set of vertical clamps **104** to constrain vertical sides of the recycled wood workpiece **115** at the input side of the chassis **102**.

(51) In this implementation, the input roller **106**, the output roller **107**, and the set of (e.g., two, four) adjustable clamps cooperate to receive and retain the recycled wood workpiece **115**—in six degrees of freedom—during the processing cycle. Additionally, the set of rollers and the set of adjustable clamps cooperate to: receive and retain the recycled wood workpiece **115** during the processing cycle; and permit fastener extractor modules to access and remove fasteners— embedded and/or extending above surfaces of the recycled wood workpiece **115** occupying the work volume **109**—during a fastener removal cycle.

(52) For example, at a first time, the local controller **170** can trigger the conveyor **105** to rotate the input roller **106** to locate a section of the recycled wood workpiece **115** cantilevered within the work volume **109** of a fastener extractor module—and therefore a set of fasteners extending above this section of the recycled wood workpiece **115**—as the system **100** autonomously scans this section of the recycled wood workpiece **115** with a set of optical sensors **110**. The local controller **170** can then: actuate a set of lateral clamps **103** to constrain lateral sides of the recycled wood workpiece **115** at the input side of the chassis **102**; and actuate a set of vertical clamps **104** to constrain vertical sides of the recycled wood workpiece **115** at the input side of the chassis **102**. Thus the set of lateral clamps **103** and the set of vertical clamps **104** enable a fastener extractor module to remove fasteners from this section of the recycled wood workpiece **115** during the fastener removal cycle. At a second time, the local controller **170** can: trigger the conveyor **105** to rotate the input roller **106** to and the output roller **107** to locate the section of the recycled wood workpiece **115** outside the fastener extractor module toward a next fastener extractor module. Additionally, the input roller **106** can locate a next section of the recycled wood workpiece **115** within the work volume **109** of the fastener extractor module—and therefore a next set of fasteners extending above this section of the recycled wood workpiece **115**—as the system **100** autonomously scans this section of the recycled wood workpiece **115** with the set of optical sensors **110**. The local controller **170** can repeat these methods and techniques for each other fastener in the

sets of fasteners and for each other section of the recycled wood workpiece **115** to remove fasteners from the recycled wood workpiece **115**.

(53) 4.4 Optical Sensor

(54) The system further includes an optical sensor **110** and/or a set of (e.g., two, three) optical sensors **110** coupled to each fastener extractor module (e.g., non-threaded fastener extractor module **120**, threaded fastener extractor module **130**). The optical sensor **110** faces the work volume **109** and is configured to capture a set of images of the work volume **109** occupied by the recycled wood workpiece **115** during a processing cycle and/or fastener removal schedule.

(55) Furthermore, the primary controller **160** can access the set of images of the work volume **109** from each optical sensor **110**, in the set of optical sensors **110**, and stitch these images into a 3D point cloud of the work volume **109** based on: placement of each optical sensor within the coordinate system of the fastener extractor module (e.g., non-threaded fastener extractor module **120**, threaded fastener extractor module **130**); and analogous overlapping features in images recorded by each optical sensor **110**, in the set of optical sensors **110**.

(56) 4.5 Non-threaded Fastener Extractor Module

(57) Each non-threaded fastener extractor module **120** includes: a stage **121** (or "a multi-axis stage"); a non-threaded fastener end effector **122**; a set of module actuators; and a local controller **170**. The multi-axis stage **121** is arranged in a work volume **109** defined by the chassis **102** and faces the recycled wood workpiece **115**. The non-threaded fastener end effector **122** is supported by the multi-axis stage **121**, which includes a lateral stage and a longitudinal stage. The non-threaded fastener end effector **122** includes: a bearing plate **123**; and a vertical stage **124** arranged on the multi-axis stage **121** and configured to support the bearing plate **123**, advance the bearing plate **123** toward a non-threaded fastener in a recycled wood workpiece **115** occupying the work volume **109**, and retract the bearing plate **123** to withdraw the non-threaded fastener from the recycled wood workpiece **115**. The non-threaded fastener end effector **122** also includes: a jaw head **126** arranged on and rotationally coupled to a distal end of the bearing plate **123**; a set of jaws **128** pivotably coupled to a distal end of the jaw head **126**; a yaw actuator **127** arranged on the bearing plate **123**, coupled to the jaw head **126**, and configured to pan (i.e., rotate) the jaw head **126** about a yaw axis of the non-threaded fastener end effector **122**; and a jaw actuator **125** arranged on the vertical stage **124**, coupled to the set of jaws **128** via a jaw linkage including a gear and configured to close the set of jaws **128** to engage the set of jaws **128** against the non-threaded fastener and to open the set of jaws **128** to release the non-threaded fastener from the set of jaws **128**.

(58) 4.6 Threaded Fastener Extractor Module

(59) Each threaded fastener extractor module **130** includes: a multi-axis stage **131**; a threaded fastener end effector **132**; a set of module actuators; and a local controller **170**. The multi-axis stage **131** is arranged in a work volume **109** defined by the chassis **102** and faces the linear sled stage. The threaded fastener end effector **132** is supported by the multi-axis stage **131** and includes: a housing **134**; a ram **136** arranged and configured to rotate in the housing **134**; a set of jaws **139** arranged on a distal end of the ram **136**; a jaw actuator **138** configured to close the set of jaws **139** against the threaded fastener; and a ram actuator **137** (e.g., drive motor) configured to rotate the ram **136** on the housing **134**. The set of module actuators is configured to manipulate the multi-axis stage **131**. The local controller **170** is configured to selectively actuate the set of module actuators, the jaw actuator **138**, and the ram actuator **137** to engage and remove the threaded fastener from the recycled wood workpiece **115** based on the fastener removal schedule.

(60) 4.7 Multiple End Effectors Per Work Volume

(61) In one variation, each non-threaded fastener extractor module **120** can include multiple independently-operable instances of the non-threaded fastener end effector **122** such as: two, three, or four instances of the non-threaded fastener end effector **122** distributed radially about the non-threaded fastener extractor module **120** in each work volume **109**; and that cooperate to access and remove non-threaded fasteners from all four sides of a section of a recycled wood workpiece **115**

occupying the work volume **109**.

(62) Similarly, each threaded fastener extractor module **130** can include multiple independently operable instances of the threaded fastener end effector **132** such as: two, three, or four instances of the threaded fastener end effector **132** distributed radially about the threaded fastener extractor module **130** in each work volume **109**; and that cooperate to access and remove threaded fasteners from all four sides of a section of a recycled wood workpiece **115** occupying the work volume **109**.

(63) For example, a first non-threaded fastener end effector **122** and/or threaded fastener end effector **132** faces a first side of the section of the recycled wood workpiece **115** within the work volume **109** of the fastener extractor module and the set of jaws **128**, **139** are configured to engage and retain metal fasteners (e.g., nails, staples, screws) from the first side of the section of the recycled wood workpiece **115**. In this example, the fastener extractor module includes a second stage **121**, **131** supported by the chassis **102**, a second non-threaded fastener end effector **122**, and/or threaded fastener end effector **132**: facing a second side orthogonal to the first side of the section of the recycled wood workpiece **115** within the work volume **109**; supported and manipulated on the chassis **102** via the second stage **121**, **131**; including a second set of jaws **128**, **139** configured to engage and retain metal fasteners (e.g., nails, staples, screws) from the second side of the section of the recycled wood workpiece **115**; and including a second jaw actuator **125**, **138** configured to actuate the second set of jaws **128**, **139**. The local controller **170** of the fastener extractor module can access a second image of the work volume **109** captured by the optical sensor **110** and based a second set of features detected in the second image: detect a second fastener in the second side of the section of the recycled wood workpiece **115** occupying the work volume **109**; and derive a second position and a second orientation of the second fastener in the work volume **109**.

(64) The local controller **170** can then: define a second target engagement position of the second non-threaded fastener end effector **122** and/or threaded fastener end effector **132**, to engage the second fastener, based on the second position and the second orientation of the second fastener; derive a fastener extraction order for the first stage **121**, **131** and the second stage **121**, **131** based on the first engagement position and the second engagement position; trigger the second stage **121**, **131** to drive the second non-threaded fastener end effector **122** to the second target engagement position according to the extraction order; trigger the second jaw actuator **125**, **138** to drive the second set of jaws **128**, **139** to engage the second fastener in the second side of the section of the recycled wood workpiece **115**; and trigger the second stage **121**, **131** to retract the second non-threaded fastener end effector **122** from the second target engagement position to extract the second fastener from the recycled wood workpiece **115**. Additionally or alternatively, the local controller **170** can: trigger the second ram actuator **137** to rotate the second ram **136** and the second set of jaws **139** about the second rotational axis of the second threaded fastener end effector **132** to retract the second fastener from the second side of the section of the recycled wood workpiece **115**.

(65) 4.7.1 Fastener Container

(66) In one variation, the system **100** includes a single fastener container **145** (e.g., waste bin) per work volume **109**, per set of non-threaded fastener extractor modules **120**, per set of threaded fastener extractor modules **130**, per individual non-threaded fastener extractor module **120**, or per individual threaded fastener extractor module **130**. In one implementation, the fastener container **145** includes a break beam or motion sensor configured to detect release of a fastener—from a threaded fastener extractor module **130** and/or a non-threaded fastener extractor module **120**—into the fastener container **145** at the conclusion of each fastener removal cycle.

(67) For example, the system **100** can include a fastener container **145** (e.g., a waste bin): arranged below the chassis **102**; defining an aperture; and configured to store extracted fasteners from the recycled wood workpiece **115**. The fastener container **145** can include a break beam sensor coupled to the fastener container **145** and configured to output a signal corresponding to motion across the aperture. In this example, the local controller **170** of the non-threaded fastener extractor module

120 and/or the threaded fastener extractor module **130** can: trigger the jaw actuator to disengage the set of jaws to release a fastener into the fastener container **145**; and confirm extraction of the fastener into the fastener container **145** in response to the break beam sensor detecting motion across the aperture within a threshold duration (e.g., 10 seconds, 20 seconds, 30 seconds) of release of the set of jaws **128**, **139** by the jaw actuator **125**.

(68) 4.8 Metal Scan Module

(69) The metal scan module **150** is configured to capture a sequence of metal scan data of the recycled wood workpiece **115** as the local controller **170** of a non-threaded fastener extractor module **120** and/or a threaded fastener extractor module **130** drives the recycled wood workpiece **115** past the metal scanner during a last segment of the processing cycle. Alternatively, the metal scan module **150** is configured to capture a set of metal scans of the recycled wood workpiece **115** as the machine (e.g., forklift) or a human operator drives the recycled wood workpiece **115** from a fastener extractor module to the metal scan module **150**.

(70) In one implementation, the metal scan module **150** includes a one-dimensional metal line scanner arranged over (or facing laterally across) the recycled wood workpiece **115**. In this implementation, the metal scanner can transmit an electromagnetic field into the recycled wood workpiece **115** to detect any fasteners (e.g., metal objects) that went undetected during previous segments of the processing cycle. Then, in response to absence of fasteners in the recycled wood workpiece **115**, the primary controller **160** can trigger the conveyor **105** to drive the recycled wood workpiece **115** forward to a recycled wood workpiece **115** pallet and reset the conveyor **105** to a home position.

(71) Alternatively, in response to detecting a fastener and/or a set of fasteners in the recycled wood workpiece **115**, the primary controller **160** can trigger the conveyor **105** to drive the recycled wood workpiece **115** forward to a recycled wood workpiece **115** receival pallet to resect a section of the recycled wood workpiece **115** containing the fastener and/or to restart the processing cycle.

(72) In one variation, the local controller **170** of a non-threaded fastener extractor module **120** and/or a threaded fastener extractor module **130** can generate a resection schedule to resect a section of the recycled wood workpiece **115** containing the fastener. For example, in response to absence of correlation between an external feature—detected in an image captured by an optical sensor—of the section of the recycled wood workpiece **115** to an internal feature in the virtual model, the primary controller **160** can: define a bounding region containing the external feature in the image; flag the bounding region with a resection flag; generate a resection schedule to resect a subsection of the recycled wood workpiece **115** corresponding to the bounding region in the image; and assign the resection schedule to a corresponding fastener extractor module to resect the subsection of the recycled wood workpiece **115**.

(73) 4.9 Primary Controller

(74) The primary controller **160** is coupled to actuators and sensors within the system **100** and executes methods and techniques described below to process a recycled wood workpiece **115** during a processing cycle.

(75) 5. Processing Cycle

(76) In one implementation, at the start of a processing cycle, the human operator or the machine (e.g., forklift) loads a recycled wood workpiece **115** onto the conveyor **105**—and therefore the set of (e.g., two) spiked rollers—and the primary controller **160** can then actuate the set of adjustable clamps to receive and retain the recycled wood workpiece **115**. The primary controller **160** then initiates the processing cycle.

(77) 5.1. Processing Cycle: Initial Imaging

(78) The primary controller **160** can: receive a recycled wood workpiece **115** in a scan volume; access a set of X-ray scans captured by an X-ray sensor facing the scan volume occupied by the recycled wood workpiece **115**; detect a set of internal features representing metallic objects in the set of X-ray scans; and compile the first set of X-ray scans into a three-dimensional representation

(or "virtual model") of the recycled wood workpiece. A first fastener extractor module can receive a section of the recycled wood workpiece in a work volume **109**. The primary controller can then: access an image, in a set of images, captured by the optical sensor **110** arranged within the fastener extractor module; detect external features extending above the section of the recycled wood workpiece **115**; scan the virtual model to identify each external feature with an analogous internal feature; identify each external feature as a metal fastener; and generate a fastener removal schedule for each external feature.

(79) 5.2 Processing Cycle: Virtual Model

(80) The primary controller **160** compiles the set of X-ray scans into a virtual model of the recycled wood workpiece **115**, such as depicting: internal features, representing metallic objects, and defects of the recycled wood workpiece **115**.

(81) In one implementation in which the X-ray scan module includes two fixed perpendicular line scanners or an X-ray sensor that sweeps across two axes perpendicular to the recycled wood workpiece **115** as a machine (e.g., forklift) and/or human operator advances the recycled wood workpiece **115** toward a first fastener extractor module, the system **100** can: compile the sequence of X-ray scan data captured by these X-ray scanners into a three-dimensional representation (or "virtual model") of the recycled wood workpiece **115** annotated with these internal features (e.g., metallic objects and defects).

(82) Furthermore, the primary controller **160** can: access an X-ray scan of the recycled wood workpiece **115** occupying the scan volume; detect a set of internal features (i.e., set of metal fasteners) populated in the recycled wood workpiece **115**; detect a helical ridge fastener in the set of metal fasteners based on a features detected in the X-ray scan; extract an initial position and an initial orientation of the helical ridge fastener in the set of metal fasteners; correlate the features representing the helical ridge fastener with known features of threaded fasteners from a threaded fastener database; compile correlations into the virtual model (e.g., three-dimensional model) of the work volume; and label the helical ridge fastener in the virtual model with a threaded fastener type, the initial position, and the initial orientation. The primary controller **160** can then: isolate a subsection in the virtual model containing the threaded fastener label; isolate a secondary subsection of the recycled wood workpiece **115** in an image—captured by the optical sensor facing the work volume of a fastener extractor module—corresponding to the subsection in the virtual model; extract a subset of features from a region in the image depicting the secondary subsection of the recycled wood workpiece **115** in the image; identify the subset of features as a head of a first fastener detected in the image; map the initial position and initial orientation of the helical ridge fastener from the subsection of the virtual model to the fastener head identified in the image; and identify the fastener as the helical ridge fastener in response to the first position and the first orientation of the fastener—extracted from the image—matching the initial position and the initial orientation of the helical ridge fastener from the virtual model.

(83) Similarly, the primary controller **160** can implement these methods and techniques to detect a smooth shank fastener in the set of metal fasteners based on features detected in the X-ray scan; extract an initial position and an initial orientation of the smooth shank fastener in the set of metal fasteners; correlate the features representing the smooth shank fastener with known features of non-threaded fasteners from a non-threaded fastener database; compile correlations into the virtual model of the work volume; and label the smooth shank fastener in the virtual model with a non-threaded fastener type, the initial position, and the initial orientation. The primary controller **160** can then: isolate a subsection in the virtual model containing the non-threaded fastener label; isolate a secondary subsection of the recycled wood workpiece **115** in the image corresponding to the subsection in the virtual model; extract a subset of features from a region in the image depicting the secondary subsection of the recycled wood workpiece **115** in the image; identify the subset of features as a head of a fastener detected in the image; map the initial position and initial orientation of the smooth shank fastener from the subsection of the virtual model to the fastener head detected

in the image; and identify the fastener as the smooth shank fastener in response to the first position and the first orientation—extracted from the image—of the fastener matching the initial position and the initial orientation of the first smooth shank fastener.

(84) However, the primary controller **160** can implement any other method or technique to generate a representation of the internal features of the recycled wood workpiece **115** based on X-ray data collected by the X-ray scan module.

(85) 5.2 Processing Cycle: Internal Recycled Wood Workpiece Characteristics

(86) The primary controller **160** can also detect internal characteristics and features of the recycled wood workpiece **115** based on these X-ray scans, such as including: splits; holes; rot; embedded metal (i.e., metallic objects fully contained within the recycled wood workpiece **115**); knots; and/or fasteners (e.g., metallic objects that extend above surfaces of the recycled wood workpiece **115**).

(87) In one implementation, the primary controller **160**: compiles the sequence of X-ray scan data captured by these X-ray scanners into a two- or three-dimensional representation of internal features (i.e., defects) in the recycled wood workpiece **115**; and detects and extracts two-dimensional or three-dimensional constellations of features from this internal representation of the recycled wood workpiece **115**. For example, the primary controller **160** can: implement blob detection, object recognition, and/or other techniques to group individual features detected in the internal representation of the recycled wood workpiece **115** into a set of feature constellations; implement artificial intelligence and/or machine learning techniques to correlate these constellations of features with known characteristics of splits, holes, rot, embedded metal, and knots; and label these constellations of features in the internal representation of the recycled wood workpiece **115** accordingly and/or project these constellations and labels onto the virtual model.

(88) Alternatively, the primary controller **160** can access a database of template images representing various examples of these defect types, such as derived from scan data of previous recycled wood workpieces **115** processed by the system **100**. Then, for each feature constellation in this set, the primary controller **160** can: compare the feature constellation to a template image in the database; and characterize a similarity of the feature constellation to the template image. If this similarity exceeds a threshold similarity, the primary controller **160** can annotate the feature constellation with a defect type and other attributes stored in or associated with the template image.

(89) However, the primary controller **160** can implement any other method or technique to detect or characterize internal features of the recycled wood workpiece **115** based on X-ray scan data captured by the X-ray scan module.

(90) 5.4 Processing Cycle: Superficial Fasteners

(91) The primary controller **160** can also interpret types, positions, and/or orientations of fasteners on each side of the recycled wood workpiece **115** from these X-ray and optical scan data.

(92) 5.4.1. Recycled Wood Workpiece Faces

(93) In one implementation, the primary controller **160** implements plane detection techniques to detect a set of faces (e.g., six "sides") in the virtual model that are approximately perpendicular. For each face detected in the virtual model, the primary controller **160**: isolates a set of superficial points in the virtual model that represent this face; calculates a plane characterized by least error (e.g., shortest Euclidean distance) between the plane and the set of superficial points; and stores the plane as a ground plane of this face in the virtual model.

(94) In another implementation, the primary controller **160**: implements plane detection techniques to detect a set of faces (e.g., six sides) in the virtual model that are approximately perpendicular; retrieves virtual recycled wood workpiece **115** geometry, such as a virtual rectangular cuboid (or virtual rectangular prism); projects the virtual recycled wood workpiece **115** geometry onto the virtual model; resizes and warps (e.g., curve) faces of the virtual recycled wood workpiece **115** geometry to minimize error between each face of the virtual recycled wood workpiece **115** geometry and points representing the corresponding faces of the virtual model; and stores the faces of the first recycled wood workpiece **115** geometry as ground planes of the faces in the virtual

model.

(95) For example, the primary controller **160** can detect a set of faces of the recycled wood workpiece **115** in the virtual model and access a template geometry representing geometry of known faces of the recycled wood workpiece **115**. Then, for each face in the set of faces, the primary controller **160** can: isolate a set of superficial points of the face in the virtual model; project the template geometry of a known face onto the set of superficial points of the face in the virtual model; calculate an offset distance between the template geometry of the known face and the set of superficial points of the face in the virtual model; and, in response to the offset distance falling below a threshold offset distance, store the template geometry of the known face as a ground plane of the face in the virtual mode.

(96) 5.4.2 Fastener Locations

(97) In one implementation, for a first face in the virtual model, the primary controller **160**: scans the virtual model for discrete clusters of points extending above the ground plane of the first face and representing internal features; and labels each cluster of points representing an internal feature as a possible fastener.

(98) Then, for a first cluster of points representing a first possible fastener, primary controller **160** can: isolate a first subset of points—representing a shank of an initial internal feature—intersecting (e.g., nearest) the ground plane of the first face in the virtual model; calculate a first centroid of the first subset of points; isolate a second subset of points of a first plane—representing a head of the initial internal feature (e.g., the top surface of a flat head of a nail or a top surface of a flat head of a screw or a top surface of a connecting segment and/or leg of a staple)—within a threshold distance of the ground plane of the first face (e.g., furthest from the ground plane of the first face); calculate a second centroid of the second subset of points; and calculate a first vector—such as within a coordinate system of the virtual model—between the first subset of points and the second subset of points based on the first and second centroids. The primary controller **160** can then label the first cluster of points in the virtual model with the first vector, representing an initial orientation and an initial position of the head of the initial internal feature.

(99) The primary controller **160** repeats this process for each other cluster of points representing possible fasteners and repeats this process for each other side of the virtual model to annotate all possible recycled wood workpieces **115**, their orientations, and their head or connecting segment locations.

(100) 4.2 Fastener Type+Virtual Model

(101) Generally, the primary controller **160** can implement artificial intelligence, template matching, computer vision techniques, and/or statistical methods, etc. to: extract a set of features from a cluster of points representing a possible fastener in the virtual model or from the optical scan data directly; and to match (or "map") the set of features to a particular fastener type.

(102) More specifically, the primary controller **160** can: detect a first subset of internal features representing metallic objects from the X-ray scans; characterize a first smoothness quality of the first subset of internal features; detect a second subset of internal features representing metallic objects from the X-ray scans; and characterize a second smoothness quality of the second subset of internal features. Then, in response to the first smoothness quality exceeding a threshold smoothness quality, the primary controller **160** can label the first subset of internal features with a non-threaded fastener type (e.g., nail, staple, nail retainer) in the virtual model. Similarly, in response to the second smoothness quality falling below the threshold smoothness quality, the primary controller **160** can label the second subset of internal features with a threaded fastener type (e.g., screw) in the virtual model.

(103) In one implementation, for each cluster of points labeled as a metallic object (e.g., possible fastener), the primary controller **160** can: detect the first face of the recycled wood workpiece **115** in the virtual model; scan the virtual model for a set of points—representing the initial metallic object—extending above a ground plane of the first face; isolate a first subset of points—

representing a head of the initial metallic object—extending above the ground plane of the first face (e.g., outside of the recycled wood workpiece **115** volume and furthest from the surface of the recycled wood workpiece **115**); characterize a depth and a breadth of the head of the initial metallic object based on the first subset of points; isolate a second subset of points—representing a shank of the initial metallic object—intersecting the ground plane of the first face in the virtual model (e.g., within the recycled wood workpiece **115** volume and further from the surface of the recycled wood workpiece **115**); and characterize a curvature of the shank of the initial metallic object based on the second subset of points. The primary controller **160** can then: calculate an aspect ratio of the head based on the depth and breadth of the head of the initial metallic object; in response to the aspect ratio exceeding a threshold aspect ratio and in response to the curvature of the shank of the initial metallic object exceeding a threshold curvature, identify the fastener type of the initial metallic object as a bent nail; annotate the set of points in the virtual model with a bent nail fastener type; and flag the set of points in the virtual model with a bent nail removal flag.

(104) The primary controller **160** can also: characterize an aspect ratio of the width versus depth of the head; characterize an angle of the side of head; and characterize a curvature of the shank fastener, such as a) proportional to an error between the cluster of points that represent the fastener and the vector that defines the predicted orientation of the fastener or b) based on a radius of an arc projected onto the virtual model characterized by least error between the cluster of points that represent the fastener and the arc. Accordingly, the primary controller **160** can identify the possible fastener as a screw if: the aspect ratio is low; the head angle indicates that the head defines a countersunk profile; and/or if the curvature is less than a threshold radius. Otherwise, the primary controller **160** can identify the fastener as a nail.

(105) The primary controller **160** can then: annotate a cluster of points in the virtual model identified as a screw with a screw removal flag; and similarly annotate a cluster of points in the virtual model identified as a nail with a nail removal flag.

(106) In yet another implementation, for each cluster of points labeled as a metallic object (e.g., possible fastener), the primary controller **160** can: detect the first face of the recycled wood workpiece **115** in the virtual model; scan the virtual model for a set of points—representing the initial metallic object—extending above a ground plane of the first face; isolate a first subset of points—representing a crown or body of the initial metallic object—extending above the ground plane of the first face; isolate a second subset of points—representing a first leg of the initial metallic object—orthogonal to the first subset of points and intersecting the ground plane of the first face (e.g., within the recycled wood workpiece **115** volume and adjacent the first subset of points); isolate a third subset of points—representing a second leg of the initial metallic object— orthogonal to the first subset of points and opposite the second subset of points intersecting the ground plane of the first face; and characterize a dimension of the initial metallic object based on the first, second, and third subsets of points representing the first leg, the crown, and the second leg. The primary controller **160** can then, in response to the dimension of the initial metallic object exceeding a threshold dimension: identify the fastener type of the initial metallic object as a staple; annotate the set of points in the virtual model with a staple fastener type; and flag the set of points in the virtual model with the staple removal flag.

(107) 5.4.4 Fastener Data from X-Ray Scans

(108) In the variation described above in which the X-ray scanner captures 3D X-ray data of the recycled wood workpiece **115**, the primary controller **160** can also assimilate superficial 3D optical data representing a fastener and adjacent internal X-ray data representing a metallic object into one composite representation of the fastener. The primary controller **160** can then implement methods and techniques described above to: detect a first cluster of X-ray-based points representing the distal end of the fastener—embedded in the recycled wood workpiece **115**—in the virtual model; calculate a first centroid of the first cluster of points; isolate a second cluster of optical-based points furthest from the ground plane of the corresponding face of the virtual model; calculate a second

centroid of the second cluster of optical-based points; calculate a vector—such as within a coordinate system of the virtual model—extending between the first and second centroids; and store this vector as the orientation of the fastener.

(109) In a similar implementation, the primary controller **160** can: calculate an arc characterized by minimum error (e.g., minimum aggregate Euclidean distance) between the arc and X-ray- and optical-based points that represent the fastener in the virtual model; calculate a tangent of this arc at its intersection with the ground plane of the corresponding face in the virtual model; and store a vector—defining this tangent in the coordinate system of the virtual model—as the orientation of the fastener.

(110) In this variation, the primary controller **160** can also verify or predict the fastener type based on the X-ray scan data. In one implementation, the primary controller **160**: identifies a cluster of points in the X-ray scan data depicting a cylindrical metallic object within the volume of the recycled wood workpiece **115** (and contiguous with a fastener identified about a ground plane of a face in the virtual model); identifies this cluster of points as a shank or barrel of a fastener; and characterizes a smoothness quality of the shank or barrel of the fastener. For example, the primary controller **160** can: map a sawtooth pattern onto the cluster of points, such as extending between the distal and proximal ends of the fastener as described above; calculate an amplitude and frequency of the sawtooth pattern that minimizes an error (e.g., a Euclidean distance) between the sawtooth pattern and the cluster of points; and characterize smoothness of the fastener inversely proportional to the amplitude and frequency. The primary controller **160** can then: identify the fastener as a nail if smoothness exceeds a threshold smoothness (e.g., the amplitude and frequency of the projected sawtooth pattern fall below threshold values); and otherwise identify the fastener as a threaded fastener (e.g., a screw).

(111) For example, the local controller **170** can: detect a set of internal features representing metallic objects in the X-ray scans within the virtual model; access an image captured by the optical sensor **110** facing the work volume **109**; detect an external feature extending above the section of the recycled wood workpiece **115** in the image; extract a position and orientation of the external feature in the image; detect a first face of the recycled wood workpiece **115** within the virtual model containing the external feature; characterize a smoothness quality of the first internal feature corresponding to the external feature based on the virtual model; and, in response to the smoothness quality exceeding a threshold smoothness quality, identify the external feature as a nail embedded in the first face of the recycled wood workpiece **115**. The local controller **170** can then: define a target engagement position for a non-threaded fastener end effector **122** (e.g., nail extractor end effector), associated with a non-threaded fastener extractor module **120** (e.g., nail fastener extractor module), to engage the nail embedded in the first face of the recycled wood workpiece **115** based on the position and orientation of the nail; and derive a nail removal schedule for the non-threaded fastener end effector **122** to remove the nail from the first face of the recycled wood workpiece **115** at the target engagement position.

(112) Alternatively, in response to the smoothness quality falling below a threshold smoothness quality, the local controller **170** can identify the external feature as a screw embedded in the first face of the recycled wood workpiece **115**. The local controller **170** can then: define a target engagement position for a threaded fastener end effector **132** (e.g., screw extractor end effector), associated with a threaded fastener extractor module **130** (e.g., screw fastener extractor module), to engage the screw embedded in the first face of the recycled wood workpiece **115** based on the position and orientation of the screw; and derive a screw removal schedule for the threaded fastener end effector **132** to remove the screw from the first face of the recycled wood workpiece **115** at the target engagement position.

(113) In one variation, the primary controller **160** can: extract a profile of the cluster of points from the X-ray scan data; implement template matching to match the profile to a stored nail or threaded fastener profile; and/or implement artificial intelligence to identify a fastener type corresponding to

this profile. In this variation, the primary controller **160** can then fuse this X-ray-based predicted fastener type with an optical-based predicted fastener type of an adjacent or contiguous fastener detected above the ground plane on the corresponding side of the virtual model to refine or verify the type of the fastener. For example, the primary controller **160** can: implement methods and techniques described above to derive a first fastener type prediction based on images from the optical sensor representing external features of the recycled wood workpiece **115**; implement these methods and techniques to derive a second fastener type prediction based on X-ray scan data representing internal features of the recycled wood workpiece **115**; and combine (or "fuse") the first and second fastener type predictions into a final prediction for the type of the fastener, such as by calculating a combination of these predictions weighted by their corresponding confidence scores.

(114) The primary controller **160** can implement this process for each other fastener and/or embedded metal detected in the X-ray scan and/or the virtual model.

(115) 5.4.5 Processing Cycle: Recycled Wood Workpiece Quality from X-Ray Scans

(116) The primary controller cam also characterize an aggregate quality of the whole recycled wood workpiece **115** proportional to its total length and inversely proportional to: quantity of splits, length of splits, proximity of splits to the longitudinal center of the recycled wood workpiece **115**; size and quantity of through and blind holes; length of recycled wood workpiece **115** containing rot and proximity of rot to the longitudinal center of the recycled wood workpiece **115**; frequency of embedded metal and proximity of embedded metal to the longitudinal center of the recycled wood workpiece **115**; frequency and size of knots; and/or frequency of fasteners in the recycled wood workpiece **115**. Then, if the aggregate quality of the whole recycled wood workpiece **115** exceeds a threshold aggregate quality, the primary controller can generate a fastener removal schedule as described below to remove fasteners without removing sections of the recycled wood workpiece **115** or otherwise cutting down the length of the recycled wood workpiece **115**. Otherwise, the primary controller can isolate discard segments to remove (or "resect") from the recycled wood workpiece **115** to increase aggregate quality of the remaining target segments of the recycled wood workpiece **115**.

(117) In one implementation, the primary controller segments the total length of the recycled wood workpiece **115** into segments of a unit length (e.g., one inch). For each segment of the recycled wood workpiece **115**, the primary controller implements methods and techniques described above to: detect a set of defects present in this segment of the recycled wood workpiece **115**; and calculate segment quality of this segment of the recycled wood workpiece **115** based on the types and scopes (e.g., sizes of holes, depths of splits, porosity from dry rot, quantity of fasteners). If the segment quality of a segment is less than a threshold segment quality, the primary controller can locate a set of resection flags on the virtual model to define removal of this segment from the recycled wood workpiece **115**.

(118) Furthermore, if the combined (e.g., average) quality of any contiguous sequence of segments of the recycled wood workpiece **115** is less than a threshold segment group quality, the primary controller can locate a set of resection flags on the virtual model for removal of this contiguous sequence of segments.

(119) The primary controller can then prescribe sub-lengths of the recycled wood workpiece **115** between this set of resection flags. For each sub-length of the recycled wood workpiece **115**, the primary controller **160** can: implement methods and techniques described above to recalculate an aggregate quality of the sub-length; flag the sub-length in the virtual model for fastener removable and reclamation (e.g., up-recycling back into a full-length recycled wood workpiece **115**) if the aggregate quality of the sub-length exceeds the threshold aggregate quality and a minimum length (e.g., one foot); and/or flag the sub-length in the virtual model for fastener removal and recycling (e.g., down-cycling into OSB or MDF) if the aggregate quality of the sub-length is less than the threshold aggregate quality and/or less than the minimum length (e.g., one foot) and the primary

controller detects no embedded metal inside the segment (i.e., absence of metal not connected to a nail or screw head at or above the surface of the recycled wood workpiece **115**). Otherwise, if the aggregate quality of the sub-length is less than the threshold aggregate quality and/or less than the minimum length (e.g., one foot) and if the primary controller detects metal fully embedded in the segment, the primary controller **160** can flag the sub-length in the virtual model for discard (and no fastener removal).

(120) 5.4.6 Fastener Removal Schedule

(121) Therefore, the primary controller **160** can execute the foregoing methods and techniques to: generate a virtual model representing internal and/or external features of the recycled wood workpiece **115**; detect locations, orientations, and types of fasteners on the recycled wood workpiece **115**; characterize quality of the recycled wood workpiece **115**; identify segments of the recycled wood workpiece **115** to discard; and annotate the virtual model with cut locations for discarding recycled wood workpiece **115** segments and removing fasteners.

(122) The primary controller **160** can then: define a target engagement position for an extractor end effector, of a fastener extractor module corresponding to a type of each fastener, to engage each fastener embedded within and/or extending above the section of the recycled wood workpiece based on position and orientations of each fastener; and generate a fastener removal schedule executable by the system **100** to selectively remove fasteners from the recycled wood workpiece **115**. More specifically, the primary controller **160** can generate a fastener extraction order— containing fastener removal schedules for each fastener extractor module—that assigns each fastener, flagged for removal in the virtual model, for removal by one fastener extractor module of the corresponding fastener type at a target engagement position; and prescribes a tool path to each flagged fastener for its removal, such as based on the type and the orientation of each flagged fastener.

(123) 6. Variation: Sled Based Conveyance+Optical Scan Module

(124) One variation of the system **100** includes: a chassis **102**; a sled; a sled actuator; a sled position sensor; an X-ray scanner; an optical scanner; a set of fastener extractor modules (e.g., non-threaded fastener extractor modules **120**, threaded fastener extractor modules **130**); a metal scanner; and a primary controller **160**.

(125) 6.1 Chassis

(126) The chassis **102**: defines a work volume **109** and includes an exo-structure arranged about each non-threaded fastener extractor module **120** and/or each threaded fastener extractor module **130**. The exo-structure is configured to: support the stage of a non-threaded fastener extractor module **120** and/or a threaded fastener extractor module **130**; and support the extractor end effector of a non-threaded fastener module **120** and/or a threaded fastener extractor module **130**.

(127) In one implementation, the chassis **102**: supports the linear sled stage, which extends from the entry of the chassis **102** to the exit of the chassis **102**; and includes an exo-structure arranged about the linear sled stage and configured to support arrays (e.g., columns) of fastener extractor modules about the linear sled stage.

(128) In one variation, the chassis **102** includes: an assembly of extruded metal profiles (e.g., aluminum, steel) that form a set of cuboid exoskeletons arranged in series. Each cuboid exoskeleton can: define a work volume **109** (e.g., operating theater); include mounting points for a fastener extractor module, scanner, or other actuator; and support the linear sled stage proximal the sagittal axis of the cuboid exoskeleton. In this implementation, the linear sled stage can extend: from a first work volume **109** (e.g., containing the X-ray scanner) at the entry of the system **100** to a last work volume **109** (e.g., containing the metal scanner) at the exit of the system **100**.

(129) However, the chassis **102** can define any other structure or arrangement of elements.

(130) 6.2 Sled

(131) The sled rides on the linear sled stage and includes a set of clamps configured to receive and retain a recycled wood workpiece **115** during a processing cycle as the system **100** autonomously

scans the recycled wood workpiece **115** with the X-ray and optical scanners and then removes fasteners from the recycled wood workpiece **115**.

(132) In one implementation, the sled includes: a set of standoffs **108** that rise above the stage to offset the recycled wood workpiece **115** above the stage and thus permit the scanners and fastener extractor modules to visually access and remove fasteners from (most of) the surface of the recycled wood workpiece **115** facing the stage during the processing cycle; and an adjustable clamp arranged on each standoff and configured to retain a section of the recycled wood workpiece **115** against its corresponding standoff.

(133) 6.2.1 Sled Actuator+Sled Position Sensor

(134) The sled actuator is configured to drive the sled—and the recycled wood workpiece **115** clamped thereto—through the series of work volumes **109** from the entry of the chassis **102** toward the exit of the chassis **102** during a processing cycle.

(135) In one implementation, the sled actuator includes a stepper or servo motor coupled to the linear sled stage via a belt or lead screw. In this implementation, the primary controller **160** can track the position of the sled—and therefore the recycled wood workpiece **115**—along the linear sled stage based on angular rotations or positions of the stepper or servo motor.

(136) In another implementation, the sled includes a linear encoder coupled to or integrated into the linear sled stage. In this implementation, the primary controller **16***o* can track or read the longitudinal position of the linear sled stage—and therefore the recycled wood workpiece **115**—within the system **100** from this linear encoder.

(137) 6.3 X-Ray Scanner

(138) The X-ray scanner is arranged on the chassis **102** proximal the entry of the chassis **102** and is configured to capture a sequence of X-ray scan data of the recycled wood workpiece **115** at the sled as the sled actuator drives the recycled wood workpiece **115** past the X-ray scanner during a first segment of the processing cycle.

(139) In one implementation, the X-ray scanner includes a one-dimensional X-ray line scanner arranged over (or facing laterally across) the linear sled stage between the entry of the chassis **102** and the optical scanner. In this implementation, the X-ray scanner can capture a series of X-ray line scans of the recycled wood workpiece **115** as the sled actuator drives the sled and the recycled wood workpiece **115** forward past the X-ray scanner. The primary controller **160** can then compile these X-ray line scans—based on cotemporal positions of the sled on the linear sled stage—into a two-dimensional X-ray scan of the recycled wood workpiece **115**.

(140) In another implementation, the X-ray scanner includes: a one-dimensional X-ray line scanner; and an X-ray stage configured to sweep the X-ray scanner between a position located over and a position facing laterally across the linear sled stage. In this implementation, the X-ray scanner can capture a first series of X-ray line scans through a sagittal axis of the recycled wood workpiece **115** and a second series of X-ray line scans through a lateral axis of the recycled wood workpiece **115** as the sled actuator drives the sled and the recycled wood workpiece **115** forward past the X-ray scanner. The primary controller **160** can then compile these X-ray line scans—based on cotemporal positions of the sled on the linear sled stage—into a three-dimensional X-ray scan of the recycled wood workpiece **115**.

(141) In a similar implementation, the X-ray scanner includes: a first one-dimensional X-ray line scanner arranged over the linear sled stage between the entry of the chassis **102** and the optical scanner; and a second one-dimensional X-ray line scanner arranged facing laterally across the linear sled stage between the entry of the chassis **102** and the optical scanner. In this implementation, the X-ray scanner can capture: a first series of X-ray line scans through a sagittal axis of the recycled wood workpiece **115** via the first X-ray scanner; and a second series of X-ray line scans through a lateral axis of the recycled wood workpiece **115** via the second X-ray scanner. The primary controller **160** can then compile these X-ray line scans—based on cotemporal positions of the sled on the linear sled stage—into a three-dimensional X-ray scan of the recycled

wood workpiece **115**.

(142) In the foregoing implementations, the X-ray scanner can alternatively include a two-dimensional X-ray scanner, and the primary controller **160** can implement similar methods and techniques to stitch two-dimensional X-ray scans—captured by the X-ray scanner—into a two- or three-dimensional X-ray scan of the recycled wood workpiece **115**.

(143) 6.4 Optical Scan Module

(144) The optical scan module is similarly arranged proximal the X-ray scanner opposite the entry of the chassis **102** and is configured to capture a sequence of optical scan data of the recycled wood workpiece **115** during a second segment of the processing cycle following the first segment of the processing cycle.

(145) In one implementation, the optical scan module includes a one-dimensional color (e.g., RGB, multispectral) line scanner arranged over (or facing laterally across) the linear sled stage between the entry of the chassis **102** and the optical scanner. In this implementation, the optical scan module can capture a series of optical line scans of the recycled wood workpiece **115** as the sled drives the sled and the recycled wood workpiece **115** forward past the optical scanner. The primary controller **160** can then compile these optical line scans—based on cotemporal positions of the sled on the linear sled stage—into a two-dimensional optical scan of the recycled wood workpiece **115**.

(146) In another implementation, the optical scan module includes: a one-dimensional color line scanner; and an optical stage configured to sweep the optical scanner between a position located over and a position facing laterally across the linear sled stage. In this implementation, the optical scan module can capture a first series of optical line scans through a sagittal axis of the recycled wood workpiece **115** and a second series of optical line scans through a lateral axis of the recycled wood workpiece **115** as the sled drives the sled and the recycled wood workpiece **115** forward past the optical scanner. The primary controller **160** can then compile these optical line scans—based on cotemporal positions of the sled on the linear sled stage—into a three-dimensional optical scan of the recycled wood workpiece **115**.

(147) In a similar implementation, the optical scan module includes: a first one-dimensional color line scanner arranged over the linear sled stage between the entry of the chassis **102** and the optical scanner; and a second one-dimensional optical line scanner arranged facing laterally across the linear sled stage between the entry of the chassis **102** and the optical scanner. In this implementation, the optical scan module can capture: a first series of optical line scans through a sagittal axis of the recycled wood workpiece **115** via the first optical scanner; and a second series of optical line scans through a lateral axis of the recycled wood workpiece **115** via the second optical scanner. The primary controller **160** can then compile these optical line scans—based on cotemporal positions of the sled on the linear sled stage—into a three-dimensional optical scan of the recycled wood workpiece **115**.

(148) In the foregoing implementations, the optical scan module can additionally or alternatively include: a structured light camera (configured to output RGB-D depth maps and point clouds); a two-dimensional color or hyperspectral camera; a stereoscopic color camera; a depth camera; and/or a thermographic camera; etc. The primary controller **160** can implement similar methods and techniques to stitch these two- and/or three-dimensional optical scans—captured by the optical scanner—into a two- or three-dimensional virtual representation of the recycled wood workpiece **115** (e.g., a "virtual model").

(149) 6.5 Fastener Extractor Modules

(150) In this variation, the system **100** also includes a set of fastener extractor modules, each: mounted to the exo-structure between the optical scanner and the exit of the chassis **102**; including an end effector configured to engage a fastener on the recycled wood workpiece **115**; and including a set of actuators configured to manipulate the end effector, on the exo-structure of the chassis **102**, to retract the fastener from the recycled wood workpiece **115** during a third segment of the processing cycle.

(151) In particular, each fastener extractor module: is configured to mount within a work zone defined by the chassis **102**; includes an end effector configured to engage a particular type of fastener (e.g., a screw, a nail, a staple); and configured to navigate the end effector—independently of the other fastener extractor modules—to target and remove fasteners of a corresponding type in a segment of the recycled wood workpiece **115** occupying the same work volume **109**, as further described below.

(152) 6.6 System Configuration

(153) In one configuration, the chassis **102** and the sled: are configured to retain and manipulate a single recycled wood workpiece **115** up to 30 feet in length, two recycled wood workpieces **115** up to 15 feet in length, or three recycled wood workpieces **115** up to 10 feet in length, etc.; and include an arrangement of clamps to retain such combinations of recycled wood workpiece **115** lengths. In this implementation, the primary controller **160** executes processes described below for each recycled wood workpiece **115** concurrently located on the sled during one processing cycle.

(154) In this configuration, the system **100** can include a series of eight work volumes **109** behind the X-ray scanner, including: a first row of four threaded fastener (e.g., screws) removal modules arranged overhead the linear sled stage, each exhibiting an actuation radius of 3 feet over the linear sled stage; a first row of four non-threaded fastener (e.g., nails, staples) removal modules arranged overhead the linear sled stage, interposed between the four threaded fastener extractor modules **130**, and each exhibiting an actuation radius of 3 feet over the linear sled stage; and similar rows of interleaved threaded fastener (e.g., screw) extractor modules **130** and non-threaded fastener (e.g., nails, staples) extractor modules **120** to the left of, to the right of, and under the linear sled stage.

(155) However, the system **100** can define a series of work volumes **109** supporting any other arrangement of scanners and fastener extractor modules of any other size and/or configured to process recycled wood workpieces **115** or other wood products in any other size or format.

(156) 6.7 Processing Cycle

(157) In this variation, at the start of a processing cycle, the primary controller **160** resets the sled to a home position at the entry of the chassis **102**. An human operator or a machine (e.g., forklift) then loads a recycled wood workpiece **115** onto the sled and clamps the recycled wood workpiece **115** to the sled. Alternatively, once the recycled wood workpiece **115** is placed on the sled, the primary controller **160** can automatically trigger the clamps to close onto the recycled wood workpiece **115**. The primary controller **16***o* then implements methods and techniques described above to initiate the processing cycle.

(158) 6.7.1 Processing Cycle: Initial Imaging

(159) The primary controller **160** then: triggers the sled actuator to drive the sled forward along the X-ray and optical scan modules; tracks the position of the sled relative to the X-ray and optical scan modules; and collects a series of X-ray and optical (e.g., color, depth) images of the recycled wood workpiece **115** from sensors arranged within these modules as the recycled wood workpiece **115** passes through the field of view of each sensor.

(160) 6.7.2 Processing Cycle: Virtual Model

(161) The primary controller **160** then compiles this series of optical scan data into a three-dimensional representation (or "virtual model") of the recycled wood workpiece **115**, such as depicting: external surfaces (e.g., top, bottom, front, back, left, and right external surfaces) of the recycled wood workpiece **115**; and volumetric representations of fasteners that extend above the external surfaces of the recycled wood workpiece **115**.

(162) In one implementation, the primary controller **160** implements image stitching techniques to assemble depth and color images—captured by the optical scanner—and concurrent positions of the sled into a "virtual model."

(163) In one variation, the primary controller **160** further projects the X-ray scan data onto the three-dimensional representation of the recycled wood workpiece **115** to populate the virtual model with internal features and defects of the recycled wood workpiece **115**. In one implementation in

which the X-ray scanner defines a fixed line or two-dimensional scanner facing a single side of the sled (e.g., arranged over and facing downward toward the sled), the system **100** can: compile the sequence of X-ray scan data into a two-dimensional representation of internal features (i.e., defects) in the recycled wood workpiece **115**—projected onto a plane normal to the focal axis of the X-ray scanner; and project the two-dimensional representation of internal features in the recycled wood workpiece **115** onto the three-dimensional representation of the recycled wood workpiece **115**.

(164) In another implementation in which the X-ray scanner includes two fixed perpendicular line scanners or an X-ray scanner that sweeps across two axes perpendicular to the sled as the sled advances the recycled wood workpiece **115** toward the first fastener extractor module, the system **100** can: compile the sequence of X-ray scan data captured by these X-ray scanners into a three-dimensional representation of internal features (i.e., defects) in the recycled wood workpiece **115**; and align and insert the three-dimensional representation of internal features in the recycled wood workpiece **115** into the three-dimensional representation of the recycled wood workpiece **115**.

(165) However, the primary controller **160** can implement any other method or technique to generate a representation of the exterior surfaces of the recycled wood workpiece **115** based on X-ray and/or optical scan data collected by the X-ray scanner and optical sensors **110**.

(166) 6.8 Fastener Removal Schedule

(167) Therefore, the primary controller **160** can execute the foregoing methods and techniques to: generate a virtual model representing internal and/or external features of the recycled wood workpiece **115**; detect locations, orientations, and types of fasteners on the recycled wood workpiece **115**; characterize quality of the recycled wood workpiece **115**; identify segments of the recycled wood workpiece **115** to discard; and annotate the virtual model with cut locations for discarding recycled wood workpiece **115** segments and removing fasteners.

(168) In one configuration of the system **100** described above, the system **100** includes a series of operating modules behind the X-ray scanner, including: a row of threaded fastener (e.g., screw) removal modules, interposed with non-threaded fastener extractor modules **120**, and each exhibiting an actuation radius of 3 feet overhead the linear sled stage; and a similar set of threaded fastener (e.g., screw) removal modules, interposed with non-threaded fastener extractor modules **120**, on the left side of, on the right side of, and under the linear sled stage.

(169) In this configuration, the primary controller **160** can initialize a fastener removal schedule. The primary controller **160** can also calculate a first sled position that: locates a trailing end of the recycled wood workpiece **115** under (or near) a first column of threaded fastener extractor modules **130** arranged about the sled within a threshold distance of the optical scanner; and locates a leading end of the recycled wood workpiece **115** under (or near) a last column of threaded fastener extractor modules **130** arranged about the sled near the exit of the system **100**. The primary controller **160** similarly: calculates a recycled wood workpiece **115** offset between a coordinate system of the recycled wood workpiece **115**—assigned in the recycled wood workpiece **115** module—and a global coordinate system of the system **100** when the sled advances to a first sled position; and writes a first code—to move the sled to the first sled position—to the fastener removal schedule.

(170) The primary controller **160** then assigns: removal of flagged screws in a top surface of a first segment of the recycled wood workpiece **115** to the first threaded fastener extractor module **130** above the sled; removal of flagged screws in the top surface of a second segment of the recycled wood workpiece **115** to a second threaded fastener extractor module **130** above the sled; removal of flagged screws in the top surface of a third segment of the recycled wood workpiece **115** to a third threaded fastener extractor module **130** above the sled; removal of flagged screws in the left surface of the first segment of the recycled wood workpiece **115** to a first threaded fastener extractor module **130** left of the sled; and removal of flagged screws in the bottom surface of the fourth segment of the recycled wood workpiece **115** to a fourth threaded fastener extractor module **130** below the sled.

(171) For a first flagged screw in the top surface of the first segment of the recycled wood workpiece **115** assigned to the first threaded fastener extractor module **130** over the linear sled stage, the primary controller **160** can calculate a position and orientation of the first screw in a first extractor coordinate system of the first threaded fastener extractor module **130** based on: a position (of the head of) and orientation of the first screw in the coordinate system of the virtual model; the offset between the recycled wood workpiece **115** coordinate system and the global coordinate system in the first sled position; and the offset between the recycled wood workpiece **115** coordinate system and the first extractor coordinate system. The primary controller **160** can then: locate a first predefined (or "canned") threaded fastener removal cycle relative to the position (of the head of) and orientation of the first screw in the first extractor coordinate system; and assign this first predefined threaded fastener removal cycle to the first threaded fastener extractor module **130** when the sled occupies the first sled position.

(172) The primary controller **160** can repeat this process for each other flagged screw in the top surface of the first segment of the recycled wood workpiece **115** assigned to the first threaded fastener extractor module **130**.

(173) The primary controller **160** can then: sort or order the corresponding threaded fastener removal cycles from nearest the entry of the system **100** to the exit (or vice versa); write codes for this batch of threaded fastener removal cycles, assigned to the first threaded fastener extractor module **130**, to the fastener removal schedule; and repeat this process to calculate and order threaded fastener removal cycles for groups of flagged fasteners in each other segment and side of the recycled wood workpiece **115** relative to coordinate systems of their corresponding threaded fastener extractor modules **130**.

(174) In this configuration, the primary controller **160** can then calculate a second sled position that: locates a trailing end of the recycled wood workpiece **115** under (or near) a first column of non-threaded fastener extractor modules **120** arranged about the sled just aft of the optical scanner; and locates a leading end of the recycled wood workpiece **115** under (or near) a last column of non-threaded fastener extractor modules **120** arranged about the sled near the exit of the system **100**. The primary controller **160** can then: calculate a recycled wood workpiece **115** offset between a coordinate system of the recycled wood workpiece **115**—assigned in the recycled wood workpiece **115** module—and a global coordinate system of the system **100** when the sled advances to the second sled position; and write a second code—to move the sled to the second sled position—to the fastener removal schedule.

(175) Accordingly, the primary controller **160** can assign: removal of flagged nails and/or staples in a top surface of the first segment of the recycled wood workpiece **115** to the first non-threaded fastener extractor module **120** above the sled; removal of flagged nails and/or staples in the top surface of the second segment of the recycled wood workpiece **115** to a second non-threaded fastener extractor module **120** above the sled; removal of flagged nails and/or staples in the top surface of the third segment of the recycled wood workpiece **115** to a third non-threaded fastener extractor module **120** above the sled; . . . removal of flagged nails and/or staples in the left surface of the first segment of the recycled wood workpiece **115** to a first non-threaded fastener extractor module **120** left of the sled; . . . and removal of flagged nails and/or staples in the bottom surface of the fourth segment of the recycled wood workpiece **115** to a fourth non-threaded fastener extractor module **120** below the sled.

(176) For a first flagged nail and/or staple in the top surface of the first segment of the recycled wood workpiece **115** assigned to the first nail extraction module over the linear sled stage, the primary controller **160** can calculate a position and orientation of the first nail and/or staple in a first extractor coordinate system of the first non-threaded fastener extraction module based on: a position (e.g., of the head of a nail, a connecting segment and/or leg of a staple) and orientation of the first nail and/or staple in the coordinate system of the virtual model; the offset between the recycled wood workpiece **115** coordinate system and the global coordinate system in the second

sled position; and the offset between the recycled wood workpiece **115** coordinate system and the first extractor coordinate system. Accordingly, the primary controller **160** can locate a first predefined (or "canned") nail and/or staple extraction cycle relative to the position (of the head of a nail, a connecting segment and/or leg of a staple) and orientation of the first nail and/or staple in the first extractor coordinate system; and assign this first predefined nail and/or staple extraction cycle to the first non-threaded fastener module when the sled occupies the first sled position.

(177) The primary controller **160** can repeat this process for each other flagged nail and/or staple in the top surface of the first segment of the recycled wood workpiece **115** assigned to the first non-threaded fastener extraction module.

(178) The primary controller **160** can then: sort or order the corresponding nail and/or staple extraction cycles from nearest the entry of the system **100** to the exit (or vice versa); write codes for this batch of nail and/or staple extraction cycles, assigned to the first non-threaded fastener extraction module, to the fastener removal schedule; and repeat this process to calculate and order nail and/or staple extraction cycles for groups of flagged fasteners in each other segment and side of the recycled wood workpiece **115** relative to coordinate systems of their corresponding non-threaded fastener extraction modules.

(179) Therefore, in this configuration, the primary controller **160** can define and order threaded fastener removal cycles simultaneously executable by up to sixteen threaded fastener extractor modules **130** arranged about the linear sled stage to remove all accessible (e.g., superficial) screws from the recycled wood workpiece **115** while the recycled wood workpiece **115** and linear sled stage occupy the first sled positions. Similarly, the primary controller **160** can define and order nail and/or staple extraction cycles simultaneously executable by up to sixteen non-threaded fastener extractor modules **120** arranged about the linear sled stage to remove all accessible (e.g., superficial) nails and/or staples from the recycled wood workpiece **115** while the recycled wood workpiece **115** and linear sled stage occupy the second sled positions.

(180) The primary controller **160** can implement similar methods and techniques to define cut paths for one or more saws mounted to the chassis **102** or mark lines for one or more cut marking modules mounted to the chassis **102**.

(181) Alternatively, the primary controller **160** can: coordinate simultaneous removal of fasteners by threaded fastener and non-threaded fastener extractor modules **120**; and/or coordinate multiple advancements of the sled to locate segments of the recycled wood workpiece **115** in particular work volumes **109** for fastener removal by threaded fastener and/or non-threaded fastener extractor modules **120** mounted in these work volumes **109**. The primary controller **160** can then compile these moves and extraction cycles into the fastener removal schedule.

(182) 7. Non-Threaded Fastener Extractor Module

(183) As described above, the system **100** can include a set of non-threaded fastener extractor modules **120** for removing non-threaded fasteners embedded within and/or extending above a recycled wood workpiece **115**. Each non-threaded fastener extractor module **120** includes: a multi-axis stage **121**; a non-threaded fastener end effector **122**; a set of module actuators; and a local controller **170**.

(184) 7.1 Gantry and Actuators

(185) In one implementation, the multi-axis stage **121** includes a three-axis gantry (e.g., X-, Y-, and Z-axes): supported by the chassis **102**; arranged in a work volume **109** over a section of the linear sled stage; configured to face (e.g., is arranged over, under, or adjacent) one side of a recycled wood workpiece **115** loaded onto the sled; and configured to support the non-threaded fastener end effector **122** over a range of vertical, lateral, and longitudinal positions to enable the non-threaded fastener end effector **122** to access non-threaded fasteners (e.g., nails, staples) in a range of positions and orientations on an adjacent side of the recycled wood workpiece **115**.

(186) In this implementation, a set of actuators can include a set of stepper or servo motors coupled to and configured to independently actuate each axis of the stage **121**, such as via a belt or

leadscrew. Furthermore, the non-threaded fastener extractor module **120** can include a set of position sensors—such as rotary or linear encoders coupled to the set of actuators or directly to the stage **121**, respectively of each non-threaded fastener extractor module **120**. The local controller **170** can track the position of each axis of the stage **121** via these position sensors and interpolate the three-dimensional position of the non-threaded fastener end effector **122**—mounted to the third axis of the gantry—within the work volume **109** based on the combined positions of these axes of the stage **121**.

(187) For example, the three-axis gantry is arranged in the work volume **109** and facing a first side of the recycled wood workpiece **115** loaded onto the conveyor **105**. A position sensor is mounted to the three-axis gantry and configured to output signals representing positions of the three-axis gantry. In this example, the local controller **170** can then: interpret a set of positions of the three-axis gantry based on positions of the three-axis gantry detected by the position sensor; and interpolate a three-dimensional position—such as a surge position, a heave position, and a sway position (e.g., (x,y,z) position within the coordinate system of the non-threaded fastener extractor module **120**)—of the non-threaded fastener end effector **122** within the work volume **109** based on the set of positions.

(188) In another implementation, the stage **121** includes a robotic arm, such as a three-link robotic arm with base rigidly mounted to the chassis **102** and configured to reach the full length and width of the near side of a segment of a recycled wood workpiece **115** occupying the work volume **109**. In this implementation, the set of actuators are configured to manipulate joints between the base and links of the robotic arm.

(189) In a similar implementation, the stage **121** includes: a single-axis gantry arranged over (or adjacent, under) and parallel to the linear sled stage; and a two-link robotic arm mounted to the gantry and configured to cooperate with the gantry to reach the full length and width of the near side of a segment of a recycled wood workpiece **115** occupying the work volume **109**. In this implementation, the set of actuators are configured to manipulate the gantry and joints between links of the robotic arm to reach the non-threaded fastener end effector **122** throughout the scope of the work volume **109**.

(190) Furthermore, the non-threaded fastener extractor module **120** can include a set of position sensors—such as linear or rotary encoders—coupled to joints of the robotic arm and/or to axes of the gantry of each non-threaded fastener extractor module **120**. The local controller **170** can track the position of the distal end of the robotic arm—and therefore, the non-threaded fastener end effector **122**—within the work volume **109** based on the positions of joints of the robotic arm and the position of the gantry within the work volume **109**.

(191) However, the multi-axis stage **121** can define any other configuration or arrangement of actuators and supporting structures.

(192) 7.2 Non-Threaded Fastener End Effector

(193) As described above, the non-threaded fastener end effector **122** is supported by the multi-axis stage **121** and includes: a bearing plate **123**; a vertical stage **124** arranged on the multi-axis stage **121** and configured to advance the bearing plate **123** toward a non-threaded fastener in a recycled wood workpiece **115** occupying the work volume **109** and to retract the bearing plate **123** to withdraw the non-threaded fastener from the recycled wood workpiece **115**; a jaw head **126** arranged on and rotationally coupled to a distal face of the bearing plate **123**; a set of jaws **128** pivotably coupled to a distal end of the jaw head **126**; a yaw actuator **127** arranged on the bearing plate **123**; and a jaw actuator **125** arranged on the vertical stage **124**, coupled to the set of jaws **128** via a jaw linking and configured to close the set of jaws **128** to engage the set of jaws **128** against the non-threaded fastener and to open the set of jaws **128** to release the non-threaded fastener from the set of jaws **128**.

(194) 7.2.1 Vertical Stage

(195) In one implementation, the vertical stage **124**: is pivotably coupled to a distal end of the

multi-axis stage **121**; defines a jaw actuator mount configured to support and locate the jaw actuator **125**; and includes a set of fixed standoffs **108** concentric with a W-axis of the jaws **128**, the set of fixed standoffs **108** configured to receive a set of fixed rods. The set of fixed rods define distal ends pivotably coupled to the set of fixed standoffs **108** and proximal ends coupled to the bearing plate **123**. The vertical stage **124** is also configured to support a bearing plate **123**, advance the bearing plate **123** toward a non-threaded fastener in a recycled wood workpiece **115** occupying the work volume **109**, and retract the bearing plate **123** to withdraw the non-threaded fastener from the recycled wood workpiece **115**.

(196) 7.2.2 Jaw Actuator

(197) The non-threaded fastener end effector **122** can include an electromechanical, pneumatic, or hydraulic jaw actuator **125**: arranged on the vertical stage **124**; coupled to the set of jaws **128** via a jaw linking including a gear; and configured to close the set of jaws **128** to engage the set of jaws **128** against the non-threaded fastener and to open the set of jaws **128** to release the non-threaded fastener from the set of jaws **128**.

(198) 7.2.3 Bearing Plate+Yaw Actuator+Jaw Head

(199) The bearing plate **123** includes: a proximal face configured to fasten distal ends of the set of fixed standoffs **108** and a distal end of the jaw actuator **125** to mount the jaw actuator **125** to the bearing plate **123**; and a distal face opposite the proximal face. The jaw head **126** is rotationally coupled to the distal face of the bearing plate **123** via a thrust-bearing, the thrust-bearing configured to transfer a rotational force into the jaw head **126** to rotate the set of jaws **128** (e.g., Y-axis rotation, yaw) to a target orientation with no or minimal torque.

(200) The yaw actuator **127** is arranged on the proximal face of the bearing plate **123**, coupled to the jaw head **126**, and configured to rotate the jaw head **126** about a yaw axis of the non-threaded fastener end effector **122**.

(201) 7.2.4 Thrust Bearing+Gear

(202) The non-threaded extractor end effector can also include a thrust bearing: interposed between the jaw head **126** and the set of jaws **128** of the non-threaded fastener end effector **122**. The non-threaded fastener end effector **122** can also include a gear interposed between the distal face of the bearing plate **123** and the jaw head **126**.

(203) 7.2.5 Jaws

(204) The non-threaded fastener end effector **122** also includes a set of (e.g., two, three) jaws **128**, each jaw **128** coupled to the jaw head **126** via a set of jaw pivots. The set of jaws **128** are operable in: a closed position to clamp against and retain a shaft and/or shank of a non-threaded fastener and to transfer a force into the non-threaded fastener to retract the non-threaded fastener from a recycled wood workpiece **115** during a non-threaded fastener removal cycle; and an open position to release the non-threaded fastener, such as into a fastener container **145** following completion of the non-threaded fastener removal cycle.

(205) For example, each jaw **128** can include a hardened steel jaw **128** with a sharpened jaw surface configured to engage and retain a shaft and/or shank of a non-threaded fastener flush with a surface of a recycled wood workpiece **115**, extending above the surface of the recycled wood workpiece **115**, and/or extending below the surface of the recycled wood workpiece **115**.

(206) Therefore, at the start of a non-threaded fastener removal cycle, the local controller **170** can: autonomously navigate the non-threaded fastener end effector **122** to a target engagement position, via the multi-axis stage **121**, and a target jaw position, via the yaw actuator **127**, predicted by the local controller **170** to contain a shaft and/or shank of a non-threaded fastener. The vertical stage **124** can then advance the bearing plate **123** toward the non-threaded fastener in a recycled wood workpiece **115** occupying the work volume **109**. The jaw actuator **125** can close the set of jaws **128** to engage the set of jaws **128** against the non-threaded fastener with a target clamping force and to open the set of jaws **128** to release the non-threaded fastener from the set of jaws **128**. Upon completion of the non-threaded fastener retraction cycle, the vertical stage **124** can retract the

bearing plate **123** toward the vertical stage **124** and open the set of jaws **128** to release the non-threaded fastener from the set of jaws **128** into a fastener container **145** at the end of the non-threaded fastener removal cycle.

(207) 7.3 W-Axis Home Position

(208) In one implementation, the vertical stage **124**: is mounted to the distal end of the multi-axis stage **121** via a linear slide; and is operable over a range of linear positions on the linear slide parallel to a W-axis of rotation of the jaws **128**.

(209) For example, the jaw actuator **125** can include a pneumatic piston coupled to a pressure reservoir and an exhaust via a set of valves. At the start of a non-threaded fastener removal cycle, the local controller **170**: activates a first valve to supply pressurized air to the jaw actuator **125**, which drives the jaw actuator **125** forward on the linear slide to stop at maximum extension; triggers the set of jaws **128** to close; and then closes the first valve and opens a second value to enable air in the jaw actuator **125** to vent to ambient, thereby reducing or eliminating forward force on the set of jaws **128**. The local controller **170** can then activate the jaw actuator **125** to retract the bearing plate **123** toward the vertical stage **124** and the set of jaws **128** engaged with a non-threaded fastener—the latter of which backs out of the recycled wood workpiece **115** and thus drives the bearing plate **123** up the vertical stage **124**.

(210) The non-threaded fastener end effector **122** can also include a linear encoder, a set of home switches, or other position sensors coupled to the jaw actuator **125**, the vertical stage **124**, the jaw head **126**, or the set of jaws **128**. During a non-threaded fastener extraction cycle, the local controller **170** can: track the position of the jaw actuator **125** on the vertical stage **124** via the position sensor; track an offset distance between the jaws **128** during a non-threaded fastener removal cycle and detect extraction of a non-threaded fastener from a recycled wood workpiece **115** based on retraction of the bearing plate **123** to withdraw the non-threaded fastener from the recycled wood workpiece **115**; detect removal of a non-threaded fastener (or failure of the non-threaded fastener) from a recycled wood workpiece **115** based on retraction of the bearing plate **123** toward the vertical stage **124** followed by the bearing plate **123** reaching a static linear position on the vertical stage **124** (and based on minimal or no load on the jaw actuator); and/or detect jaw slippage on a non-threaded fastener or inadvertent engagement of a threaded fastener based on absence of retraction of the bearing plate **123** toward the vertical stage **124** based on low load on the jaw actuator **125** and/or based on an offset distance between the set of jaws **128**—detected by the linear position sensor—falling below an offset distance threshold.

(211) In one implementation, the non-threaded fastener end effector **122** can include: a force sensor coupled to the set of jaws **128** and configured to output a first signal corresponding to a clamping force of the set of jaws **128**; and a position sensor coupled to the jaw actuator **125**, facing the set of jaws **128**, and configured to output a second signal corresponding to an offset distance between each jaw **128** in the set of jaws **128**. In this implementation, the local controller **170** can: interpret a first clamping force of the set of jaws **128** based on the first signal; interpret a first offset distance between each jaw **128** in the set of jaws **128** based on the second signal; and identify engagement of the set of jaws **128** with the fastener in the section of the recycled wood workpiece **115**, in response to the first clamping force falling below a clamping force threshold and in response to the first offset distance exceeding an offset distance threshold.

(212) Alternatively, the force sensor is configured to output a third signal corresponding to the clamping force of the set of jaws **128** and the position sensor is configured to output a fourth signal corresponding to the offset distance between each jaw **128** in the set of jaws **128**. The local controller **170** can then: interpret a second clamping force of the set of jaws **128** based on the third signal; interpret a second offset distance between each jaw **128** in the set of jaws **128** based on the fourth signal; and identify jaw slippage of the set of jaws **128** with the fastener in the section of the recycled wood workpiece **115**, in response to the first clamping force falling below the clamping force threshold and in response to the first offset distance falling below the offset distance

threshold.

(213) 7.4 Non-Threaded Fastener Extractor Module: Degrees of Freedom

(214) As described above, the multi-axis stage **121** is operable in three degrees of freedom to locate the non-threaded fastener end effector **122** over a range of positions within the work volume **109**. The non-threaded fastener end effector **122** is pivotably coupled to the distal end of the multi-axis gantry via the vertical stage **124**. Accordingly, the local controller **170** can drive the multi-axis stage **121** and the yaw actuator **127** to locate the jaws **128** adjacent (e.g., spanning) the shaft and/or shank of a non-threaded fastener protruding above a side of a recycled wood workpiece **115**.

(215) Furthermore, the non-threaded fastener end effector **122** can include a yaw actuator **127** to trigger a gear to transfer a rotational force to rotate the jaw head **126** and the set of jaws **128** (e.g., Y-axis rotation, yaw) according to a target orientation. The yaw actuator **127** thus defines a further degree of freedom of the non-threaded fastener end effector **122**. Additionally, the non-threaded fastener end effector **122** includes a jaw actuator **125** configured to open and close the jaws **128** independently of the rotation of the jaws **128**, and thus defines yet another degree of freedom of the non-threaded fastener end effector **122**. Accordingly, the local controller **170** can actuate the jaw actuator **125** to clamp the jaws **128** against a non-threaded fastener extending above an adjacent side of the recycled wood workpiece **115**.

(216) Therefore, the multi-axis stage can support and locate the non-threaded fastener end effector **122** in three degrees of freedom. The jaw actuator locates the jaws in a translational degree of freedom (e.g., heave) and the yaw actuator **127** in a further rotational degree of freedom (e.g., yaw). Thus, the non-threaded fastener end effector **122** can support and locate the jaws **128** in five degrees of freedom.

(217) However, the elements of the non-threaded fastener end effector **122** described above can be arranged in any other configuration to similarly support and locate the jaws in five degrees of freedom.

(218) 7.5 Non-Threaded Fastener Removal Cycle

(219) In one implementation, once a section of a recycled wood workpiece **115** enters a work volume **109** of a non-threaded fastener extractor module **120**, the local controller **170** calculates a position and predicted orientation of a non-threaded fastener—on the section of the recycled wood workpiece **115** (e.g., super surface, flush with the surface of the recycled wood workpiece **115**, subsurface)—within a local coordinate system of the non-threaded fastener extractor module **120** based on: the position of the non-threaded fastener within the coordinate system of the virtual model; the predicted orientation of the non-threaded fastener, within the coordinate system of the virtual model, derived from the virtual model; the longitudinal position of the section of the recycled wood workpiece **115** within a global coordinate system of the system Dm; and/or a known or stored position of the local coordinate system of the non-threaded fastener extractor module **120** relative to the global coordinate system. The local controller **170** also triggers the jaw actuator to fully advance and open the set of jaws.

(220) Additionally, the local controller **170** can: interpolate the position of the set of jaws **128** and the orientation of the set of jaws **128** of the non-threaded fastener extractor module **120** within the local coordinate system based on positions of the multi-axis stage **121**, the linear stage, etc. and based on an orientation of the gear; and autonomously navigate the multi-axis stage **121** and the gear to locate the set of jaws **128** adjacent (e.g., spanning) a segment of the non-threaded fastener extending above the adjacent surface of the recycled wood workpiece **115** and to locate the W-axis of the set of jaws **128** coaxial with the predicted orientation of the non-threaded fastener.

(221) The local controller **170** can then: trigger the jaw actuator **125** to close the jaws **128**, thereby clamping the jaws **128** onto the non-threaded fastener; and trigger the vertical stage **124** to retract the bearing plate **123**, thereby extracting the non-threaded fastener from the recycled wood workpiece **115**.

(222) Furthermore, during this non-threaded fastener extraction cycle and as described above, the

local controller **170** can: actuate the vertical stage **124** to bias (or "preload") the set of jaws **128** and the jaw actuator **125** away from the recycled wood workpiece **115** and thus maintain a continuous retraction force on the non-threaded fastener; track the position and offset distance of the set of jaws **128** via a linear position sensor; verify extraction of the non-threaded fastener from the recycled wood workpiece **115** responsive to retraction of the bearing plate **123** toward the vertical stage **124**; and detect removal of the non-threaded fastener from the recycled wood workpiece **115** (or failure of the non-threaded fastener) responsive to subsequent cessation or retraction of the bearing plate **123** toward the vertical stage **124**. Upon detecting removal (or failure) of the non-threaded fastener, the local controller **170** can: autonomously navigate the multi-axis stage **121** to locate the set of jaws **128** over the fastener container **145**; trigger the jaw actuator **125** to open the set of jaws **128**, thereby releasing the non-threaded fastener into the fastener container **145**; verify removal of the non-threaded fastener in response to detecting an object passing the break beam or motion sensor on the fastener container **145** within a threshold duration (e.g., one second) after triggering the jaw actuator **125** to open the set of jaws **128**; and record removal of the non-threaded fastener from the recycled wood workpiece **115**, such as by annotating a representation of the non-threaded fastener in the virtual model with a "removed" flag.

(223) The non-threaded fastener extractor module **120** can repeat this process for each other non-threaded fastener detected on the adjacent side of the recycled wood workpiece **115** occupying the work volume **109**.

(224) 7.5.1 Superficial Straight Nail Removal Cycle

(225) In one implementation, the local controller **170** can identify a straight nail normal to the surface of a recycled wood workpiece **115** occupying the work volume **109** and superficial to the recycled wood workpiece **115** (e.g., protruding above the surface of the of recycled wood workpiece **115**) based on an image of the work volume **109** captured by the optical sensor **110**.

(226) For example, the local controller **170** can: detect a straight nail superficial to a surface of section of the recycled wood workpiece **115** based on features extracted from the image; detect a shank axis and an intersection of a shank and a nail head of the straight nail based on the features; trigger the stage (e.g., multi-axis stage **121**) to drive the non-threaded fastener end effector **122** to a target engagement position to align the retraction axis of the set of jaws **128** coaxial with the axis of the straight nail; trigger the jaw actuator **125** to engage the straight nail at the intersection of the shank and the nail head (e.g., close the set of jaws **128** against the straight nail with a target clamping force, at the intersection of the shank and the nail head); trigger the stage (e.g., vertical stage **124**) to retract the non-threaded fastener end effector **122** from the target engagement position to extract the straight nail from the recycled wood workpiece **115**; and trigger the jaw actuator **125** to open the set of jaws **128** to release the straight nail into a fastener container **145**.

(227) Similarly, the local controller **170** can: extract a breadth of the nail head based on the features; calculate a centroid of the nail head based on the breadth; derive a target jaw position to locate the retraction axis of the set of jaws **128** coaxial with the centroid of the nail head; and trigger the jaw actuator **125** to open the set of jaws **128** by a distance proportional to the breadth of the head of the fastener, in response to driving the non-threaded fastener end effector **122** to the target engagement position. The local controller **170** can then implement methods and techniques described above to extract the straight nail from the recycled wood workpiece **115**.

(228) In another implementation, the local controller **170** can identify a second straight nail non-normal to the surface (e.g., angularly offset) of a recycled wood workpiece **115** occupying the work volume **109** and superficial to the recycled wood workpiece **115** (e.g., protruding above the surface of the of recycled wood workpiece **115**) based on X-ray images. The local controller **170** can then: identify an engagement point at the entry of the shank of the second straight nail into the recycled wood workpiece **115**; derive a shank axis of the second straight nail relative the recycled wood workpiece **115** based on the engagement point; calculate a target orientation for the set of jaws **128** based on the angular offset of the second straight nail; autonomously navigate the multi-axis stage

121 to align the retraction axis of the set of jaws **128** coaxial with the shank axis of the second straight nail; trigger the yaw actuator **127** to rotate the jaws **128** about the yaw axis of the non-threaded fastener end effector **122** to the target orientation; trigger the jaw actuator **125** to drive the set of jaws **128** to the engagement point and to close the set of jaws **128** against the second straight nail with a target clamping force to extract the second straight nail; trigger the vertical stage **124** to retract the bearing plate **123**; and trigger the jaw actuator **125** to open the set of jaws **128** to release the second straight nail into a fastener container **145**.

(229) The local controller **170** can implement similar methods and techniques to remove each other straight nail normal and/or non-normal and superficial (e.g., protruding above the surface of the recycled wood workpiece **115**) to each other recycled wood workpiece **115** occupying the work volume **109**.

(230) 7.5.2 Subsurface+Flush Straight Nail Removal Cycle

(231) Generally, the local controller **170** can implement the methods and techniques described above to remove a nail extending below and/or embedded within a surface of the recycled wood workpiece **115** (e.g., subsurface) and/or flush to the surface of the recycled wood workpiece **115**.

(232) In one implementation, the local controller **170** can identify a straight nail extending below the surface and/or embedded within the section of the recycled wood workpiece **115** based on an image of the work volume **109** captured by the optical sensor no. Then, the local controller **170** can: access a maximum jaw depth for removing a straight nail (e.g., 0.5 inches); and calculate a target depth of the jaws **128** to engage a shank of the nail below the nail head, such as including plunging the jaws **128** below the surface of the recycled wood workpiece **115** to clamp against the shank of the nail. In particular, in this implementation, the local controller **170** can calculate the target depth for the jaws **128** as a function of a total length of the shank of the nail, such as a target depth corresponding to a distance below the nail head derived from an X-ray or color image of the recycled wood workpiece **115** and less than the maximum jaw depth.

(233) In one variation, the local controller **170** can: access an image of the work volume **109** captured by the optical sensor **110** and identify a fastener embedded in the surface of the recycled wood workpiece **115** occupying the work volume **109** based on features extracted from the image; extract a position and orientation of a head of the fastener based on the features; access the virtual model (e.g., three-dimensional model) of the work volume **109** occupied by the recycled wood workpiece **115** labeled with fastener types, positions, and orientations; scan the three-dimensional model for a fastener; and identify the fastener in the virtual model labeled with a nail fastener type based on the position and the orientation of the head of the fastener. The local controller **170** can then identify the fastener embedded in the section of the recycled wood workpiece **115** as a nail and implement methods and techniques described above to extract the nail from the section of the recycled wood workpiece **115**.

(234) In another implementation, the local controller **170** can calculate the target depth for the jaws **128** as a function of a diameter of the head of the nail, such as a target depth corresponding to a distance below the nail head equivalent to one diameter of the nail head derived from an X-ray or color image of the recycled wood workpiece **115** and less than the maximum jaw depth. Furthermore, the local controller **170** can implement the methods and techniques described above for a straight and subsurface nail to autonomously navigate the multi-axis stage **121** and the gear to locate the set of jaws **128** adjacent (e.g., spanning) a segment of a non-threaded fastener extending below the adjacent surface of the recycled wood workpiece **115** based on the target depth of the set of jaws **128** and locate the retraction axis of the set of jaws **128** coaxial with the axis of the nail.

(235) For example, the local controller **170** can: calculate a diameter (e.g., 9/32 inches) of the head of the straight nail and a length (e.g., 2.5 inches) of the shank of the straight nail; and calculate a target depth (e.g., 0.25 inches) of the jaws **128** to open and clear the head of the straight nail and to plunge below the surface (e.g., extend into the section) of the recycled wood workpiece **115** to clamp the shank of the straight nail. The local controller **170** can then derive the target jaw position

to align the retraction axis of the set of jaws **128** coaxial with the shank axis of the straight nail; autonomously navigate the multi-axis stage **121**, the yaw actuator **127**, and the jaw actuator **125**: to clamp the jaws **128** onto the shank of the straight nail, extending below the adjacent surface of the recycled wood workpiece **115**, at the target depth (e.g., 0.25 inches) of the set of jaws **128**; to locate the retraction axis of the set of jaws **128** coaxial with the axis of the straight nail; and to extract the straight nail extending below the surface of the recycled wood workpiece **115**, along the shank axis, from the section of the recycled wood workpiece **115** (e.g., Y-axis of the non-threaded fastener extractor module **120**).

(236) 7.5.3 Superficial Bent Nail Removal Cycle

(237) In one implementation, the local controller **170** can identify a bent nail superficial to a recycled wood workpiece **115** occupying the work volume **109** (e.g., protruding above the surface of the of recycled wood workpiece **115**); derive a position and an orientation of a shank of the bent nail in the work volume **109**; and derive a curvature of the shank (e.g., shaft, shank) of the bent nail, based on features extracted from an image of the recycled wood workpiece **115** captured by the optical sensor **110**.

(238) In one variation, the local controller **170** can: identify an engagement point of the base of the shank of the bent nail entering the recycled wood workpiece **115**; derive a shank axis of the bent nail relative the recycled wood workpiece **115** based on the engagement point; calculate a target orientation for the set of jaws **128** based on the curvature of the bent nail; autonomously navigate the multi-axis stage **121** to align the retraction axis of the set of jaws **128** coaxial with the shank axis of the bent nail; trigger the yaw actuator **127** to rotate the set of jaws **128** to the target orientation; trigger the jaw actuator **125** to close the set of jaws **128** against the bent nail with a target clamping force, at the engagement point to extract the bent nail along the shank axis from the recycled wood workpiece **115**; trigger the vertical stage **124** to retract the bearing plate **123**; and trigger the jaw actuator **125** to open the set of jaws **128** to release the bent nail into a fastener container **145**.

(239) For example, the local controller **170** can: define a target engagement position of the non-threaded fastener end effector **122**, to engage the shank of the bent nail, based on the position and orientation of the bent nail within the work volume **109**; derive a shank axis of the bent nail relative a longitudinal axis of the recycled wood workpiece **115** based on the target engagement position; define a target jaw position for the set of jaws **128** based on the curvature of the bent nail; trigger the stage to drive the non-threaded fastener end effector **122** to align a retraction axis of the set of jaws **128** coaxial with the shank axis of the bent nail; trigger the jaw actuator **127** to drive the set of jaws **128** to engage the shank of the bent nail at the target jaw position; and trigger the stage to retract the non-threaded fastener end effector **122** from the target engagement position to extract the bent nail, along the shank axis, from the recycled wood workpiece **115**.

(240) 7.5.4 Subsurface+Flush Bent Nail Removal Cycle

(241) In one implementation, the local controller **170** can identify a bent nail extending below the surface of the recycled wood workpiece **115** (e.g., subsurface) occupying the work volume **109** and derive a curvature of the shank (e.g., shaft, shank) of the bent nail below the surface of the recycled wood workpiece **115**, based on an image of the recycled wood workpiece **115** captured by the optical sensor **110**.

(242) Then, the local controller **170** can: access a maximum jaw depth for removing a straight nail (e.g., 0.5 inches); and calculate a target depth of the jaws **128** to engage a shank of the bent nail below the nail head, such as including plunging the jaws **128** below the surface of the recycled wood workpiece **115** to clamp against the shank of the nail at an engagement point. In particular, in this implementation, the local controller **170** can calculate the target depth for the jaws **128** as a function of a total length of a straight segment of the shank of the nail, such as a target depth corresponding to a distance below the nail head derived from an X-ray or color image of the recycled wood workpiece **115** and less than the maximum jaw depth.

(243) In one variation, the local controller **170** can identify an engagement point of the straight segment of the shank of the bent nail closest to the surface of the recycled wood workpiece **115**; and derive a shank axis of the bent nail relative the recycled wood workpiece **115** based on the engagement point. The local controller **170** can then implement the methods and techniques described above to close the set of jaws **128** against the bent nail with a target clamping force, at the engagement point to extract the bent nail along the shank axis from the recycled wood workpiece **115**.

(244) In another variation, the local controller **170** can calculate a target retraction axis of the bent nail based on the curvature of the bent nail (e.g., 20% of the curvature of the curved nail, 30% of the curvature of the curved nail) to locate a jaw axis of the jaws **128** perpendicular to the recycled wood workpiece **115** (e.g., along the grain of the recycled wood workpiece **115**) to reduce and/or eliminate accidental splitting of the recycled wood workpiece **115** during a bent nail removal cycle. Furthermore, the local controller **170** can calculate a target depth of the jaws **128** (e.g., 0.30 inches) to plunge below the surface of the recycled wood workpiece **115** and clamp the jaws **128** onto the shank of the bent nail. Then, the local controller **170** can autonomously navigate the multi-axis stage **121** and the yaw actuator **127**: to locate the jaws **128** adjacent (e.g., spanning) the curvature of the bent nail extending below the adjacent surface of the recycled wood workpiece **115** according to the target retraction axis of the jaws **128** and the target depth of the jaws **128**; and to locate the orientation of the jaws **128** coaxial with the predicted orientation of the bent nail.

(245) For example, the local controller **170** can: detect a bent nail embedded in the section of the recycled wood workpiece **115** in the image; detect a curvature and a shank of the bent nail based on features extracted from the image of the work volume **109**; calculate a target depth for the set of jaws **128** to extend into the section of the recycled wood workpiece **115** to engage the bent nail at the engagement point, based on the shank of the bent nail; derive a shank axis of the bent nail relative the longitudinal axis of the recycled wood workpiece **115** based on the curvature of the bent nail; derive a target jaw position to align the retraction axis of the set of jaws **128** coaxial with the shank axis of the bent nail; and retract the threaded fastener end effector **132** to extract the bent nail, along the shank axis, from the section of the recycled wood workpiece **115**.

(246) Thus, the local controller **170** can trigger the jaw actuator **125** to close the set of jaws **128** against the shank of a bent nail below the surface of the recycled wood workpiece **115**, straighten the nail along the Y-axis, and extract the nail along the Y-axis of the non-threaded fastener extractor module **120** for the bent nail with minimal to no torque applied to the set of jaws **128**, thereby reducing and/or eliminating failure (e.g., slipping, snipping, missing, accidental splitting of the recycled wood workpiece **115**) during the bent nail removal cycle.

(247) However, the local controller **170** can implement similar methods and techniques to remove a bent nail flush with the surface of the recycled wood workpiece **115**.

(248) 7.5.5 Staple+Retainer Nail Removal Cycle

(249) Generally, the local controller **170** can implement the methods and techniques described above to remove a staple, extending below and/or embedded within the surface of the recycled wood workpiece **115**, according to a fastener removal schedule corresponding to a staple.

(250) In one variation, the local controller **170** can access a table (e.g., list, chart) of staple dimensions and a predefined dimension threshold for staples and access an image of the work volume **109** captured by the optical sensor **110**. Based on features extracted from the image, the local controller **170** can: detect a staple embedded in a surface of the recycled wood workpiece **115** occupying the work volume **109**; derive a dimension of the staple in the work volume **109**; and detect a first vertex (e.g., (x,y) position) of the staple defining a first height and a second vertex (e.g., (x,y) position) of the staple defining a second height less than the first height. Then, in response to the dimension of the staple falling below the threshold staple dimension, the local controller **170** can identify the staple as negligible (e.g., leave the staple within the recycled wood workpiece **115**) and move on to a next non-threaded fastener in the recycled wood workpiece **115**.

For example, the local controller **170** can access a table (e.g., list, chart) of staple dimensions and a predefined dimension threshold (e.g., 26/8 or 26 mm crown and 8 mm legs) for staples. The local controller **170** can then identify the dimension of the staple (e.g., 24/6 or 24 mm crown and 6 mm legs) based on a first leg, a crown, and a second leg—extending below the surface of the recycled wood workpiece **115**—and, in response to the dimension of the staple falling below the threshold staple dimension (e.g., 26/8 or 26 mm crown and 8 mm legs), the local controller **170** can identify the staple as negligible (e.g., leave the staple within the recycled wood workpiece **115**) and move on to a next non-threaded fastener in the recycled wood workpiece **115**.

(251) Alternatively, in response to the dimension of the staple exceeding the threshold staple dimension, the local controller **170** can: derive a vertical plane between the first vertex and the second vertex of the staple based on the first height and the second height; define a target jaw position to align the retraction axis of the set of jaws **128** of the set of jaws **128** parallel to the vertical plane between the first vertex and the second vertex of the staple; identify the first vertex within a threshold distance of the surface of the recycled wood workpiece **115** (e.g., closest to the recycled wood workpiece **115** surface) based on the first height; derive a target depth for the set of jaws **128** to engage the first vertex of the staple based on the first height; trigger the jaw actuator **125** to drive the set of jaws **128** to engage the first vertex of the staple to a target engagement position (e.g., (x,y) position) and the target jaw position according to the target depth; and trigger the stage to retract the non-threaded fastener end effector **122** from the target engagement position to extract the staple, along the vertical plane (e.g., Y-axis of the non-threaded fastener extractor module **120**), from the recycled wood workpiece **115**.

(252) For example, the local controller **170** can identify the next non-threaded fastener in the recycled wood workpiece **115** as a staple. Accordingly, the local controller **170** can identify the dimension of the staple (e.g., 28/10 or 28 mm crown and 10 mm legs) based on a first leg, a crown, and a second leg—extending below the surface of the recycled wood workpiece **115**—and, in response to the dimension of the staple exceeding the threshold staple dimension (e.g., 26/8 or 26 mm crown and 8 mm legs), the local controller **170** can detect a first vertex (e.g., 4,3) of the staple between a first point of the crown of the staple, a second point of the crown of the staple, and a third point at a distal end of a first leg of the staple, closest to the recycled wood workpiece **115** surface relative the extractor coordinate system of the non-threaded fastener extractor module **120**. The local controller **170** can also detect a second vertex of the staple between the first point of the crown of the staple, the second point of the crown of the staple, and a fourth point at a distal end of a second leg of the staple. The local controller **170** can then trigger the jaw actuator **125** to extend the jaws **128** to clamp the staple at the first vertex (e.g., 4,3) and to extract the staple along the Y-axis of the non-threaded fastener extractor module **120**.

(253) The local controller **170** can implement the methods and techniques described above to remove a staple, extending below the surface of the recycled wood workpiece **115**, according to a fastener removal schedule corresponding to a staple. However, the local controller **170** can also implement the methods and techniques described above to remove a nail retainer, extending below the surface of the recycled wood workpiece **115**, according to a fastener removal schedule corresponding to the nail retainer fastener.

(254) 7.6 Failures

(255) Generally, the primary controller **160** (or the local controller **170** in the non-threaded fastener extractor module **120**) can detect failures in the removal of non-threaded fasteners based on non-optical data captured by sensors arranged on the non-threaded fastener extractor module **120** and implement computer vision techniques to detect and distinguish common removal failures—such as slipped, snipped, missed, etc.—for each type of fastener (e.g., nail, screw, staple). The system **100** can then receive these common removal failures and update the fastener removal schedules to reduce failure of future non-threaded fasteners with analogous characteristics such as fastener type, location relative a recycled wood workpiece **115** (e.g., subsurface, super surface, flush), and/or

fastener size.

(256) In one implementation, during a non-threaded fastener removal cycle, the local controller **170** can track an applied force of the jaw actuator **125** and an offset distance between the set of jaws **128** based on sensors arranged in the non-threaded fastener end effector **122**. Then, in response to detecting absence of an offset distance between the set of jaws **128** and in response to detecting a decrease in the applied force, the local controller **170** can: identify a snipped failure of the set of jaws **128** on a non-threaded fastener; trigger the jaw actuator **125** to release the set of jaws **128**; update the target position, target orientation, and target depth for removal of the non-threaded fastener; and drive the yaw actuator **127** and the jaw actuator **125** to recenter the set of jaws **128** on the non-threaded fastener for the removal cycle.

(257) Alternatively, in response to detecting absence of an offset distance between the set of jaws **128** and in response to detecting an increase in the applied force followed by a sharp decrease, the local controller **170** can: identify a slipped failure of the set of jaws **128** on a non-threaded fastener; trigger the jaw actuator **125** to open the jaws **128**; update the target position, target orientation, and applied force for removal of the non-threaded fastener; and drive the yaw actuator **127** to rotate the jaws **128** and the jaw actuator **125** to recenter the jaws **128** on the non-threaded fastener for the removal cycle. The local controller **170** can repeat the foregoing process until the non-threaded fastener is removed from the recycled wood workpiece **115** and/or until an attempt threshold is achieved (e.g., 2 attempts, 3 attempts). Additionally, responsive to the quantity of attempts (e.g., 3 attempts) exceeding the attempt threshold (e.g., 2 attempts), the local controller **170** can identify the removal cycle as a miss failure and navigate the multi-axis stage **121** to locate the non-threaded fastener end effector **122** over the next non-threaded fastener in the recycled wood workpiece **115**.

(258) 7.7 Non-Threaded Fastener Realignment

(259) In one variation, during a non-threaded fastener removal cycle, the primary controller **160** (or the local controller **170** in the non-threaded fastener extractor module **120**) can further: monitor load and/or back EMF on the set of actuators coupled to the multi-axis stage **121**; monitor positions of the multi-axis stage **121** and the linear stage; interpret an angular offset between the axis of the non-threaded fastener and the W-axis of the jaws **128** based on positional oscillations in the non-threaded fastener extractor module **120** while the gear rotates the jaws **128**; and then drive these to alternate positions to reduce these positional oscillations, improve alignment between the axis of the non-threaded fastener and the W-axis of the jaws **128**, and thus reduce fatigue on the non-threaded fastener that may otherwise result in failure before complete removal of the non-threaded fastener from the recycled wood workpiece **115**.

(260) 8. Threaded Fastener Extractor Module

(261) As described above, the system **100** can include a set of threaded fastener extractor modules **130** for removing threaded fasteners embedded within and/or extending above a recycled wood workpiece **115**. Each threaded fastener extractor module **130** includes: a multi-axis stage **131**; a threaded fastener end effector; a set of module actuators; and a local controller **170**.

(262) In one implementation, each threaded fastener extractor module **130** is supported and manipulated on the chassis **102** via the stage, defines a rotational axis (e.g., R-axis), and includes: a ram **136** configured to rotate about the rotational axis; a ram actuator **137** configured to actuate the ram **136**; a set of jaws **139** coupled to the ram **136** and configured to engage and retain metal fasteners from the section of the recycled wood workpiece **115**; and a jaw actuator **138** configured to actuate the set of jaws **139**.

(263) 8.1 Gantry and Actuators

(264) In one implementation, the multi-axis stage **131** includes a three-axis gantry: supported by the chassis **102**; arranged in a work volume **109** over a section of the linear sled stage; configured to face (e.g., is arranged over, under, or adjacent) one side of a recycled wood workpiece **115** loaded onto the sled; and configured to support the threaded fastener end effector over a range of vertical, lateral, and longitudinal positions to enable the threaded fastener end effector to access

screws in a range of positions and orientations on the adjacent side of the recycled wood workpiece **115**.

(265) In this implementation, the threaded fastener end effector can also include two perpendicular rotational stages (e.g., B- and C-axes) arranged on the distal end of the three-axis gantry (e.g., X-, Y-, and Z-axes).

(266) The set of actuators can include a set of stepper or servo motors coupled to and configured to independently actuate each axis of the stage, such as via a belt or leadscrew. Furthermore, the threaded fastener extractor module **130** can include a set of position sensors—such as rotary or linear encoders coupled to the set of actuators or directly to the stage, respectively. The local controller **170** can track the position of each axis of the stage via these position sensors and interpolate the three-dimensional position of the threaded fastener end effector—mounted to the third axis of the gantry—within the work volume **109** based on the combined positions of these axes of the stage.

(267) For example, the three-axis gantry is arranged in the work volume **109** and facing a first side of the recycled wood workpiece **115** loaded onto the conveyor **105**. A position sensor is mounted to the three-axis gantry and configured to output signals representing positions of the three-axis gantry. In this example, the local controller **170** can then: interpret a set of positions of the three-axis gantry based on positions of the three-axis gantry detected by the position sensor; and interpolate a three-dimensional position—such as a surge position, a heave position, and a sway position (e.g., (x,y,z) position within the coordinate system of the non-threaded fastener extractor module **120**)—of the threaded fastener end effector within the work volume **109** based on the set of positions.

(268) In another implementation, the stage includes a robotic arm, such as a three-link robotic arm with base rigidly mounted to the chassis **102** and configured to reach the full length and width of the near side of a segment of a recycled wood workpiece **115** occupying the work volume **109**. In this implementation, the set of actuators are configured to manipulate joints between the base and links of the robotic arm.

(269) In a similar implementation, the stage includes: a single-axis gantry arranged over (or adjacent, under) and parallel to the linear sled stage; and a two-link robotic arm mounted to the gantry and configured to cooperate with the gantry to reach the full length and width of the near side of a segment of a recycled wood workpiece **115** occupying the work volume **109**. In this implementation, the set of actuators are configured to manipulate the gantry and joints between links of the robotic arm to reach the threaded fastener end effector throughout the scope of the work volume **109**.

(270) Furthermore, the threaded fastener extractor module **130** can include a set of position sensors —such as linear or rotary encoders—coupled to joints of the robotic arm and/or to axes of the gantry. The local controller **170** can track the position of the distal end of the robotic arm—and therefore, the threaded fastener end effector—within the work volume **109** based on the positions of joints of the robotic arm and the position of the gantry within the work volume **109**.

(271) However, the multi-axis stage **131** can define any other configuration or arrangement of actuators and supporting structures.

(272) 8.2 Threaded Fastener End Effector

(273) As described above, the threaded fastener end effector is supported by the multi-axis stage **131** and includes: a housing **134**; a ram **136** arranged in the housing **134** and operable between an extended position and a retracted position to accommodate retraction of a threaded fastener from a recycled wood workpiece **115**; a set of jaws **139** arranged on a distal end of the ram **136**; a jaw actuator **138** configured to close the set of jaws **139** against the threaded fastener; and a ram actuator **137** configured to rotate the ram **136** in the housing **134**.

(274) 8.2.1 Housing

(275) In one implementation, the housing **134**: is pivotably coupled to a distal end of the multi-axis

stage **131**; includes a set of bearing journals concentric with an R-axis of the threaded fastener end effector **132**; defines a ram actuator **137** mount configured to support and locate the ram actuator **137**; and defines a jaw actuator **138** mount configured to support and locate the jaw actuator **138**.

(276) In one variation, the housing **134** is pivotably coupled to the stage and configured to support the ram **136**. A spring **135** is arranged in the housing **134** and is configured to advance the ram **136** to a maximum extension position and retract the ram **136** to a minimum extension position.

(277) 8.2.2 Ram

(278) The ram **136**: defines an internal bore configured to support a pushrod; is supported by and configured to rotate in the set of bearing journals of the housing **134**; and includes a mesh—such as a timing belt gear or timing gear—configured to couple to the ram actuator **137**. A distal end of the ram **136**: defines a set of (e.g., two) jaw pivots; and/or defines a linear bearing configured to support a distal end of the pushrod.

(279) 8.2.3 Jaws

(280) The threaded fastener extractor module **130** also includes a set of (e.g., two, three) jaws **139**, each: pivotably coupled to a jaw pivot at the distal end of the ram **136** of each threaded fastener extractor module **130**. The set of jaws **139** are operable in: a closed position to clamp against and retain a head and/or shank of a screw and to transfer a torque (e.g., retraction force)—applied to the ram **136** by the ram actuator **137**—into the screw to retract the screw from a recycled wood workpiece **115** during a screw removal cycle; and an open position to release the screw, such as into a fastener container **145** following completion of the screw removal cycle. For example, each jaw **139** can include a hardened steel jaw with serrated jaw surface configured to engage and retain a head or shank of a screw.

(281) 8.2.4 Pushrod and Jaw Actuator

(282) The threaded fastener end effector can also include a pushrod: running inside the ram **136**; defining a distal end that runs in and is supported by the linear bearing on the distal end of the ram **136**; and coupled to each jaw **139** via a connecting rod.

(283) The jaw actuator **138** can include an electromechanical, pneumatic, or hydraulic linear actuator: mounted to the housing **134** aft of the ram **136**; and configured to advance and retract the pushrod within the ram **136**, thereby clamping and releasing the set of jaws **139** on a screw in the closed and open positions, respectfully.

(284) The threaded fastener extractor module **130** can also include: a thrust bearing—such as a captured spherical or tapered bearing—interposed between the proximal end of the pushrod and the jaw actuator **138** and configured to: transfer a linear force applied by the jaw actuator **138** into the pushrod to open or close the jaws **139**; and transmit no or minimal torque on the pushrod—such as applied by the ram actuator **137** or a screw—into the jaw actuator **138** of a threaded fastener extractor module **130**.

(285) Therefore, at the start of a screw removal cycle, the local controller **170** can: trigger the jaw actuator **138** to retract the jaws **139**, thereby opening the jaws **139** to receive a next fastener; autonomously navigate the threaded fastener end effector to a target position that the local controller **170** predicts contains a head and/or a shank of a screw; and trigger the jaw actuator **138** to advance the pushrod forward and to apply a target compressive force onto the proximal end of the pushrod, thereby driving the jaws **139** closed onto the screw and clamping the screw with a target clamping force. Upon completion of the screw retraction cycle, the local controller **170** can trigger the jaw actuator **138** to retract the pushrod, thereby opening the jaws **139** and releasing the screw.

(286) 8.3 R-axis Home Position

(287) In one implementation, the housing **134**: is mounted to the distal end of the multi-axis stage **131** via a linear slide; and is operable over a range of linear positions on the linear slide parallel to the R-axis of rotation of the ram **136** (e.g., rotational axis of the threaded fastener end effector **132**). In this implementation, the threaded fastener end effector can also include a secondary housing **134**

actuator: coupled to the housing **134** or linear slide; configured to drive the housing **134**—and therefore the ram **136**, the set of jaws **139**, etc.—forward to a home position in preparation for engaging the jaws **139** against a next screw; and configured to release forward pressure on the housing **134** to enable the housing **134** to retract from a nearby recycled wood workpiece **115** as rotation of the ram **136** extracts this screw from the recycled wood workpiece **115**.

(288) For example, the secondary housing **134** actuator can include a pneumatic piston coupled to a pressure reservoir and an exhaust via a set of valves. At the start of a screw removal cycle, the local controller **170**: activates a first valve to supply pressurized air to the housing **134** actuator, which drives the housing **134** forward on the linear slide to stop at maximum extension; triggers the jaw actuator **138** to close the jaws **139**; and then closes the first valve and opens a second value to enable air in the housing **134** actuator to vent to ambient, thereby reducing or eliminating forward force on the ram **136**. The local controller **170** can then activate the ram actuator **137** to rotate the ram **136**, the jaws **139**, and the screw—the latter of which backs out of the recycled wood workpiece **115** and thus drives the housing **134** up the linear slide.

(289) The threaded fastener end effector can also include a linear encoder, a set of home switches, or other position sensor coupled to the housing **134** or linear slide. During a screw removal cycle, the local controller **170** can: track the position of the housing **134** on the linear slide via the position sensor; detect extraction of a threaded fastener from a recycled wood workpiece **115** based on retraction of the housing **134** on the linear slide as the ram actuator **137** rotates the ram **136**; detect removal of a threaded fastener (or failure of the screw) from a recycled wood workpiece **115** based on retraction of the housing **134** on the linear slide as the ram actuator **137** rotates the ram **136** followed by the housing **134** reaching a static linear position on the linear slide (and based on minimal or no load on the ram actuator **137**); and/or detect jaw slippage on a screw or inadvertent engagement of a non-threaded fastener (e.g., a nail, a staple) based on absence of retraction of the housing **134** on the linear slide as the ram actuator **137** rotates the ram **136** and based on high load on the ram actuator **137**.

(290) For example, the local controller **170** can: trigger the ram actuator **137** to align the rotational axis of the threaded fastener end effector coaxial with the detected orientation of a non-threaded fastener; trigger the ram actuator **137** to rotate the ram **136** about the rotational axis of the threaded fastener end effector and the set of jaws **139** to retract the non-threaded fastener with the retraction force from the section of the recycled wood workpiece **115**; and trigger the stage to retract the threaded fastener end effector from the first target engagement position to remove the threaded fastener from the section of the recycled wood workpiece **115**.

(291) 8.4 Ram Actuator

(292) The ram actuator **137**: is mounted to the housing **134**; is coupled to the mesh on the ram **136**, such as via a geartrain or timing belt; and is configured to rotate the ram **136** about the R-axis. For example, the ram actuator **137** can include an electromechanical, pneumatic, or hydraulic rotary actuator.

(293) 8.5 Threaded Fastener Extractor Module: Degrees of Freedom

(294) As described above, the multi-axis stage **131** is operable in three degrees of freedom to locate the threaded fastener end effector over a range of positions within the work volume **109**. The threaded fastener end effector is pivotably coupled to the distal end of the multi-axis gantry via the two driven rotational axes—such as a two-axis gimble—operable in two additional degrees of freedom. Accordingly, the local controller **170** can drive the multi-axis stage **131** and these two driven rotational axes: to locate a rotational axis (e.g., the R-axis) of the ram **136** coaxial with a threaded fastener inset in a section of recycled wood workpiece **115** occupying the operation theater of the threaded fastener extractor module **130**; and to locate the jaws **139** adjacent (e.g., spanning) the head or shank of the threaded fastener protruding above the adjacent face of the recycled wood workpiece **115**.

(295) The ram actuator **137** in the threaded fastener end effector is configured to rotate the ram **136**

about the R-axis and thus defines a further degree of freedom of the threaded fastener end effector. Accordingly, the local controller **170** can actuate the ram actuator **137**, thereby rotating the ram **136** and the jaws **139** and retracting a threaded fastener clamped by the jaws **139**.

(296) The jaw actuator **138** is coupled to the jaws **139** via a pushrod and thrust bearing, is configured to open and close the jaws **139** independently of rotation of the ram **136** and jaws **139**, and thus defines a further degree of freedom of the threaded fastener end effector. Accordingly, the local controller **170** can actuate the jaw actuator **138** to clamp the jaws **139** against a threaded fastener extending above an adjacent side of the recycled wood workpiece **115**.

(297) Furthermore, the threaded fastener end effector is coupled to the two driven rotational axes (or to the multi-axis stage **131** more generally) via a linear slide operable over a range of linear positions parallel to the R-axis of rotation of the ram **136**. As described above, the linear slide can enable the ram **136** and housing **134** to retract from the adjacent side of a recycled wood workpiece **115** as the threaded fastener end effector removes a threaded fastener from the recycled wood workpiece **115**. Accordingly, the linear slide can define a further degree of freedom of the threaded fastener end effector.

(298) Therefore, the multi-axis stage **131** can support and locate the two driven rotational axes in three degrees of freedom. The two driven rotational axes locate the linear slide in two additional rotational degrees of freedom. The linear slide locates the housing **134** in a further translation degree of freedom. The housing **134** locates the ram **136** in an additional rotational degree of freedom and the jaw actuator **138** and pushrod in a further translational degree of freedom. Thus, the threaded fastener end effector can support and locate the jaws **139** in eight degrees of freedom.

(299) However, the threaded fastener end effector described above can be arranged in any other configuration to similarly support and locate the jaws **139** in eight degrees of freedom. For example: the multi-axis stage **131** can support and locate the two driven rotational axes in three degrees of freedom; the two driven rotational axes locate the housing **134** in two additional rotational degrees of freedom; the housing **134** locates the ram **136** in both a translational degree of freedom and a rotational degree of freedom; and the ram **136** supports the jaw actuator **138** and pushrod in a further translational degree of freedom. Therefore, in this example, the threaded fastener end effector can again support and locate the jaws **139** in eight degrees of freedom.

(300) 8.6 Screw Removal Cycle

(301) In one implementation, once a section of a recycled wood workpiece **115** enters a work volume **109** of a threaded fastener extractor module **130**, the local controller **170** calculates a position and predicted orientation of a screw—on the section of the recycled wood workpiece **115** —within a local coordinate system of the threaded fastener extractor module **130** based on: the position of the screw within the coordinate system of the virtual model; the predicted orientation of the screw, within the coordinate system of the virtual model, derived from the virtual model; the position of the section of the recycled wood workpiece **115** within a global coordinate system of the system **100**; and/or a known or stored position of the local coordinate system of the threaded fastener extractor module **130** relative to the global coordinate system. The local controller **170** also: triggers the jaw actuator **138** to open the jaws **139**; and triggers the secondary housing **134** actuator to fully advance the linear slide.

(302) The local controller **170** then: interpolates the position of the jaws **139** and the R-axis of the threaded fastener end effector **132** within the local coordinate system based on positions of the multi-axis stage **131**, the two driven rotational axes, and the linear slide, etc.; and autonomously navigates the multi-axis stage **131** and the two driven rotational axes to locate the jaws **139** adjacent (e.g., spanning) a segment of the screw extending above the adjacent surface of the recycled wood workpiece **115** and to locate the R-axis of the ram **136** coaxial with the predicted orientation of the screw.

(303) The local controller **170** then: triggers the jaw actuator **138** to close the jaws **139**, thereby clamping the jaws **139** onto the screw; triggers the secondary housing **134** actuator to release the

linear slide; and triggers the ram actuator **137** to rotate the ram **136**, thereby rotating and extracting the screw from the recycled wood workpiece **115**.

(304) Furthermore, during this screw removal cycle and as described above, the local controller **170** can: actuate the secondary housing **134** actuator to bias (or "preload") the jaws **139** and the housing **134** away from the recycled wood workpiece **115** and thus maintain a continuous retraction force on the screw; track the position of the housing **134** on the linear slide via the position sensor; track load on the ram actuator **137** (e.g., based on current draw of the ram actuator **137** or by reading a torque sensor coupled to the ram actuator **137**); verify extraction of the screw from the recycled wood workpiece **115** responsive to retraction of the housing **134** up the linear slide as the ram actuator **137** rotates the ram **136**; and detect removal of the screw from the recycled wood workpiece **115** (or failure of the screw) responsive to subsequent cessation or retraction of the housing **134** up the linear slide and a drop in load on the ram actuator **137**. Upon detecting removal (or failure) of the screw, the local controller **170** can: autonomously navigate the multi-axis stage **131** and the two driven rotational axes to locate the jaws **139** over the waste bin; trigger the jaw actuator **138** to open the jaws **139**, thereby releasing the screw into the waste bin; verify removal of the screw in response to detecting an object passing the break beam or motion sensor on the waste bin within a threshold duration (e.g., one second) after triggering the jaw actuator **138** to open the jaws **139**; and record removal of the screw from the recycled wood workpiece **115**, such as by annotating a representation of the screw in the virtual model with a "removed" flag.

(305) Furthermore, during a screw removal cycle, the primary controller **160** (or the local controller **170** in the threaded fastener extractor module **130**) can: detect jaw slippage on a screw in response to detecting absence of retraction of the housing **134** on the linear slide as the ram actuator **137** rotates the ram **136** when load on the ram actuator **137** is high; and then trigger the jaw actuator **138** to release the jaws **139**, drive the set of actuators to recenter the jaws **139** on the screw, and then repeat the foregoing process to remove the screw from the recycled wood workpiece **115**.

(306) In one implementation, the threaded fastener end effector **132** can include: a force sensor coupled to the threaded fastener end effector **132** and configured to output a first signal representing retraction force of the set of jaws **139** on a fastener during retraction of the fastener from the section of the recycled wood workpiece **115**; and a position sensor configured to output a second signal corresponding to a position of the housing **134** on the stage. In this implementation, the local controller **170** can: interpret a first retraction force of the set of jaws **139** on the first fastener based on the first signal; interpret a first position of the housing **134** based on the second signal; and confirm extraction of the fastener from the section of the recycled wood workpiece **115**, in response to the first position of the housing **134** falling within a first target position range and in response to the first retraction force of the set of jaws **139** falling below a retraction force threshold.

(307) Alternatively, the force sensor is configured to output a third signal representing retraction force of the set of jaws **139** on the fastener and the position sensor is configured to output a fourth signal corresponding to the position of the housing **134** on the stage. The local controller **170** can then: interpret a second retraction force of the set of jaws **139** on the first fastener based on the third signal; interpret a second position of the housing **134** based on the fourth signal; and identify jaw slippage of the set of jaws **139** with the fastener in the section of the recycled wood workpiece **115**, in response to the second position of the housing **134** falling within a second target position range less than the first target position range and in response to the second retraction force of the set of jaws **139** falling below the retraction force threshold.

(308) The threaded fastener extractor module **130** can repeat this process for each other screw detected on the adjacent side of the recycled wood workpiece **115** occupying the work volume **109**.

(309) 8.6.1 Superficial Screw Removal

(310) In one implementation, the local controller **170** can identify a screw non-normal to the surface of a recycled wood workpiece **115** occupying the work volume **109** and superficial to the

recycled wood workpiece **115** (e.g., protruding above the surface of the of recycled wood workpiece **115**) based on an image of the work volume **109** captured by the optical sensor **110**.

(311) For example, the local controller **170** can: access the virtual model (e.g., three-dimensional model) of the work volume **109** occupied by the recycled wood workpiece **115** labeled with fastener types, positions, and orientations; scan the virtual model for the fastener; and identify the fastener in the virtual model labeled with a screw fastener type based on the position and the orientation of the shank of the fastener; access an image of the work volume **109** occupied by the section of the recycled wood workpiece **115** and extract a set of features from the image. Then, based on the set of features in the image, the local controller **170** can: detect a screw superficial to a surface of the recycled wood workpiece **115** occupying the work volume **109**; and derive a position, an orientation, and a length of a shank of the screw in the work volume **109**. The local controller **170** can then: define a target torque of the ram actuator **137**, to rotate the ram **136** and the set of jaws **139** about the rotational axis of the threaded fastener end effector **132** to retract the screw, based on the length of the shank of the screw; define a shank axis of the screw relative a longitudinal axis of the recycled wood workpiece **115** based on the orientation of the shank of the screw; define a target engagement position of the threaded fastener end effector **132**, to engage the screw, based on the position of the shank of the screw; trigger the stage to drive the threaded fastener end effector **132** to the target engagement position; trigger the ram actuator **137** to align the rotational axis of the threaded fastener end effector **132** coaxial with the shank axis of the shank of the screw; trigger the jaw actuator **138** to drive the set of jaws **139** to engage the shank of the screw in the section of the recycled wood workpiece **115** at the target engagement position; trigger the ram actuator **137** to rotate the ram **136** and the set of jaws **139** according to the target torque, to retract the screw, along the shank axis, from the section of the recycled wood workpiece **115**; and trigger the stage to retract the threaded fastener end effector **132** from the target engagement position to remove the screw from the recycled wood workpiece **115**.

(312) 8.6.2 Subsurface+Flush Screw Removal

(313) In one implementation, the local controller **170** can identify a screw embedded within the surface and/or extending below the surface (e.g., subsurface) of a recycled wood workpiece **115** occupying the work volume **109** and flush to the recycled wood workpiece **115** based on an image of the work volume **109** captured by the optical sensor **110**. In this implementation, the local controller **170** can implement methods and techniques described above to trigger the threaded fastener end effector **132** to engage a head of the screw for removal from the recycled wood workpiece **115**.

(314) For example, the local controller **170** can: derive a position and orientation of a head of the screw in the work volume **109** based on the set of features; define a shank axis of the screw relative a longitudinal axis of the recycled wood workpiece **115** based on the orientation of the head of the screw; define a target engagement position of the threaded fastener end effector **132**, to engage the screw, based on the position of the head of the screw; trigger the stage to drive the threaded fastener end effector **132** to the target engagement position; trigger the ram actuator **137** to locate the rotational axis of the threaded fastener end effector **132** coaxial with the shank axis of the head of the screw; trigger the jaw actuator **138** to drive the set of jaws **139** to engage the head of the screw in the section of the recycled wood workpiece **115** at the target engagement position; trigger the ram actuator **137** to rotate the ram **136** and the set of jaws **139** to retract the screw, along the shank axis, from the section of the recycled wood workpiece **115**; and trigger the stage to retract the threaded fastener end effector **132** from the target engagement position to remove the screw from the recycled wood workpiece **115**.

(315) 8.7 Threaded Fastener Realignment

(316) In one variation, during a screw removal cycle, the primary controller **160** (or the local controller **170** in the threaded fastener extractor module **130**) can further: monitor torque (or load, back EMF) on the set of actuators coupled to the multi-axis stage **131**, the two driven rotational

axes, and the ram actuator **137**; monitor positions of the multi-axis stage **131**, the two driven rotational axes, and the linear slide; interpret an angular offset between the axis of the screw and the R-axis of the ram **136** based on torque and/or positional oscillations in the threaded fastener extractor module **130** while the ram actuator **137** rotates the ram **136**; and then drives these to alternate positions to reduce these torque and/or positional oscillations, improve alignment between the axis of the screw and the R-axis of the ram **136**, and thus reduce fatigue on the screw that may otherwise result in screw failure before the threaded fastener extractor module **130** fully removes the screw from the recycled wood workpiece **115**.

(317) For example, the local controller **170** can implement closed-loop controls to: serially oscillate each of the driven rotational axes and each axis of the multi-axis stage **131**, such as over narrow angular or linear position windows; and update a target position of each axis of the threaded fastener extractor module **130** to positions that yield minimum and/or most consistent torque outputs on each stage as the ram actuator **137** rotates the ram **136** to extract the screw during the screw removal cycle.

(318) In another example, the local controller **170** can track oscillation of axes within the threaded fastener extractor module **130** during a first rotation of the ram **136** during the screw removal cycle. In this example, the local controller **170** can then: pause rotation of the ram **136**; trigger the jaw actuator **138** to release the jaws **139** from the screw; implement a threaded fastener extractor module **130** model to calculate an offset between the axis of the screw and the R-axis of the ram **136** based on the verified position of the screw and oscillation of each axis of the threaded fastener extractor module **130** during the first rotation ram **136**; drive actuators in the threaded fastener extractor module **130** to reduce this offset; trigger the jaw actuator **138** to close the jaws **139** onto the screw; and resume the screw removal cycle.

(319) Alternatively, the local controller **170** can: track oscillation of axes within the threaded fastener extractor module **130** during a first rotation of the ram **136** during the screw removal cycle; pause rotation of the ram **136**; trigger the jaw actuator **138** to release the jaws **139** from the screw; characterize the range of oscillation of each axis of the threaded fastener extractor module **130**; move each axis of the threaded fastener extractor module **130** to the center position within its corresponding range of oscillations during the first rotation of the ram **136**; trigger the jaw actuator **138** to close the jaws **139** onto the screw; and then resume the screw removal cycle.

(320) In yet another example, the local controller **170** can trigger the ram actuator **137** to rotate the ram **136** and the set of jaws **139** about the rotational axis of the threaded fastener end effector **132** to retract the screw from the section of the recycled wood workpiece **115** at a first time. The local controller **170** can then: record a retraction force of the set of jaws **139**, via a force sensor arranged on the set of jaws **139**, at the first time; retract the threaded fastener end effector **132** from a target engagement position to remove the screw from the section of the recycled wood workpiece **115** at a second time succeeding the first time; record a position of the threaded fastener end effector **132**, via a position sensor arranged on the threaded fastener end effector **132**, at the second time; and, in response to the retraction force of the set of jaws **139** falling below a retraction force threshold and in response to the position of the threaded fastener end effector **132** falling within a target position range, identify removal of the fastener from the section of the recycled wood workpiece **115** at the second time.

(321) The systems and methods described herein can be embodied and/or implemented at least in part as a machine configured to receive a computer-readable medium storing computer-readable instructions. The instructions can be executed by computer-executable components integrated with the application, applet, host, server, network, website, communication service, communication interface, hardware/firmware/software elements of a user computer or mobile device, wristband, smartphone, or any suitable combination thereof. Other systems and methods of the embodiment can be embodied and/or implemented at least in part as a machine configured to receive a computer-readable medium storing computer-readable instructions. The instructions can be

executed by computer-executable components integrated by computer-executable components integrated with apparatuses and networks of the type described above. The computer-readable medium can be stored on any suitable computer readable media such as RAM 136s, ROMs, flash memory, EEPROMs, optical devices (CD or DVD), hard drives, floppy drives, or any suitable device. The computer-executable component can be a processor but any suitable dedicated hardware device can (alternatively or additionally) execute the instructions.

(322) As a person skilled in the art will recognize from the previous detailed description and from the figures and claims, modifications and changes can be made to the embodiments of the invention without departing from the scope of this invention as defined in the following claims.

Claims

1. A system for extracting fasteners from a recycled wood workpiece comprising: a chassis defining a work volume; a conveyor: configured to receive the recycled wood workpiece populated with metal fasteners; and configured to constrain a section of the recycled wood workpiece within the work volume; an optical sensor facing the work volume; a threaded fastener extractor module comprising: a stage supported by the chassis; and a threaded fastener end effector: supported and manipulated on the chassis via the stage; defining a rotational axis; and comprising: a ram configured to rotate about the rotational axis; a ram actuator configured to actuate the ram; a set of jaws coupled to the ram and configured to engage and retain metal fasteners from the section of the recycled wood workpiece; and a jaw actuator configured to actuate the set of jaws; and a controller configured to: access an image of the work volume captured by the optical sensor; based on a set of features detected in the image: detect a first fastener in the section of the recycled wood workpiece occupying the work volume; and derive a first position and a first orientation of the first fastener in the work volume; define a first target engagement position of the threaded fastener end effector, to engage the first fastener, based on the first position and the first orientation of the first fastener in the work volume; trigger the stage to drive the threaded fastener end effector to the first target engagement position; trigger the jaw actuator to drive the set of jaws to engage the first fastener in the section of the recycled wood workpiece; and trigger the ram actuator to rotate the ram and the set of jaws about the rotational axis of the threaded fastener end effector to retract the first fastener from the section of the recycled wood workpiece.

2. The system of claim 1: wherein each jaw in the set of jaws: comprises a serrated jaw surface configured to engage and retain metal fasteners from the section of the recycled wood workpiece; and configured to transfer a retraction force from the ram into metal fasteners from the section of the recycled wood workpiece; and wherein the controller is further configured to: trigger the ram actuator to align the rotational axis of the threaded fastener end effector coaxial with the first orientation of the first fastener; trigger the ram actuator to rotate the ram about the rotational axis of the threaded fastener end effector and the set of jaws to retract the first fastener with the retraction force from the section of the recycled wood workpiece; and trigger the stage to retract the threaded fastener end effector from the first target engagement position to remove the first fastener from the section of the recycled wood workpiece.

3. The system of claim 1, wherein the controller is further configured to: based on the set of features in the image: detect the first fastener comprising a screw superficial to a surface of the recycled wood workpiece occupying the work volume; and derive a second position, a second orientation, and a length of a shank of the screw in the work volume; define a target torque of the ram actuator, to rotate the ram and the set of jaws about the rotational axis of the threaded fastener end effector to retract the screw, based on the length of the shank of the screw; define a normal axis of the screw relative a longitudinal axis of the recycled wood workpiece based on the second orientation of the shank of the screw; define a second target engagement position of the threaded fastener end effector, to engage the screw, based on the second position of the shank of the screw;

trigger the stage to drive the threaded fastener end effector to the second target engagement position; trigger the ram actuator to align the rotational axis of the threaded fastener end effector coaxial with the normal axis of the shank of the screw; trigger the jaw actuator to drive the set of jaws to engage the shank of the screw in the section of the recycled wood workpiece at the second target engagement position; trigger the ram actuator to rotate the ram and the set of jaws according to the target torque, to retract the screw, along the normal axis, from the section of the recycled wood workpiece; and trigger the stage to retract the threaded fastener end effector from the second target engagement position to remove the screw from the recycled wood workpiece.

4. The system of claim 1: further comprising a force sensor coupled to the threaded fastener end effector and configured to output a first signal representing retraction force of the set of jaws on the first fastener during retraction of the first fastener from the section of the recycled wood workpiece; wherein the threaded fastener end effector further comprises: a housing pivotably coupled to the stage and configured to support the ram; and a position sensor configured to output a second signal corresponding to a position of the housing on the stage; and wherein the controller is configured to: interpret a first retraction force of the set of jaws on the first fastener based on the first signal; interpret a first position of the housing based on the second signal; and confirm extraction of the first fastener from the section of the recycled wood workpiece, in response to the first position of the housing falling within a first target position range and in response to the first retraction force of the set of jaws falling below a retraction force threshold.

5. The system of claim 4: wherein the force sensor is configured to output a third signal representing retraction force of the set of jaws on the first fastener; wherein the position sensor is configured to output a fourth signal corresponding to the position of the housing on the stage; and wherein the controller is configured to: interpret a second retraction force of the set of jaws on the first fastener based on the third signal; interpret a second position of the housing based on the fourth signal; and identify jaw slippage of the set of jaws with the first fastener in the section of the recycled wood workpiece, in response to the second position of the housing falling within a second target position range less than the first target position range and in response to the second retraction force of the set of jaws falling below the retraction force threshold.

6. The system of claim 1: further comprising a fastener container: arranged below the chassis; defining an aperture; and configured to store extracted fasteners from the recycled wood workpiece; further comprising a break beam sensor: coupled to the fastener container; and configured to output a signal corresponding to motion across the aperture; and wherein the controller is configured to: trigger the jaw actuator to disengage the set of jaws to release the first fastener into the fastener container; and confirm extraction of the first fastener into the fastener container in response to the break beam sensor indicating motion across the aperture within a threshold duration of release of the set of jaws by the jaw actuator.

7. The system of claim 1: further comprising an X-ray module defining a scan volume and comprising an X-ray sensor facing the scan volume; wherein the conveyor is configured to drive the recycled wood workpiece through the scan volume of the X-ray module; and wherein the controller is configured to: access an X-ray scan of the recycled wood workpiece occupying the scan volume; detect a set of metal fasteners populated in the recycled wood workpiece; detect a first helical ridge fastener in the set of metal fasteners based on a second set of features detected in the X-ray scan; extract an initial position and an initial orientation of the first helical ridge fastener in the set of metal fasteners; correlate the second set of features representing the first helical ridge fastener with known features of threaded fasteners from a threaded fastener database; compile correlations into a three-dimensional model of the work volume; label the first helical ridge fastener in the three-dimensional model with a threaded fastener type, the initial position, and the initial orientation; and identify the first fastener as the first helical ridge fastener in response to the first position and the first orientation of the first fastener matching the initial position and the initial orientation of the first helical ridge fastener.

8. The system of claim 7, wherein the controller is configured to: isolate a subsection in the three-dimensional model containing the threaded fastener label; isolate a secondary subsection of the recycled wood workpiece in the image corresponding to the subsection in the three-dimensional model; extract a subset of features from a region in the image depicting the secondary subsection of the recycled wood workpiece in the image; identify the subset of features as a head of the first fastener; and map the initial position and initial orientation of the first helical ridge fastener from the subsection of the three-dimensional model to the first fastener head identified in the image.

9. The system of claim 1: wherein the stage comprises a three-axis gantry: arranged in the work volume; and facing a first side of the recycled wood workpiece loaded onto the conveyor; further comprising, a position sensor configured to output signals representing positions of the three-axis gantry; and wherein the controller is configured to: interpret a set of positions of the three-axis gantry based on positions of the three-axis gantry detected by the position sensor; and interpolate a three-dimensional position of the threaded fastener end effector within the work volume based on the set of positions, the three-dimensional position of the threaded fastener end effector comprising a surge position, a heave position, and a sway position.

10. The system of claim 1, wherein the controller is further configured to: based on the set of features detected in the image: detect the first fastener comprising a screw proud to a surface of the recycled wood workpiece occupying the work volume; and derive a second position, a second orientation of a head of the screw in the work volume; and define a normal axis of the screw relative a longitudinal axis of the recycled wood workpiece based on the second orientation of the head of the screw; define a second target engagement position of the threaded fastener end effector, to engage the screw, based on the second position of the head of the screw; trigger the stage to drive the threaded fastener end effector to the second target engagement position; trigger the ram actuator to locate the rotational axis of the threaded fastener end effector coaxial with the normal axis of the head of the screw; trigger the jaw actuator to drive the set of jaws to engage the head of the screw in the section of the recycled wood workpiece at the second target engagement position; trigger the ram actuator to rotate the ram and the set of jaws to retract the screw, along the normal axis, from the section of the recycled wood workpiece; and trigger the stage to retract the threaded fastener end effector from the second target engagement position to remove the screw from the recycled wood workpiece.

11. The system of claim 1, wherein the chassis further comprises: a set of lateral clamps configured to constrain lateral sides of the recycled wood workpiece at an input side of the chassis; and a set of vertical clamps configured to constrain vertical sides of the recycled wood workpiece at the input side of the chassis.

12. The system of claim 1, wherein the conveyor comprises: an input roller: coupled to an input side of a lateral axis of the threaded fastener extractor module; and comprising a first set of standoffs: extending radially from the input roller; defining a length greater than a nominal fastener length; and configured to locate the recycled wood workpiece at the input side; and an output roller: coupled to an output side of the lateral axis of the threaded fastener extractor module; and comprising a second set of standoffs: extending radially from the output roller; defining the length greater than the nominal fastener length; and configured to locate the recycled wood workpiece at the output side.

13. The system of claim 1: wherein the threaded fastener end effector faces a first side of the section of the recycled wood workpiece within the work volume; wherein the first set of jaws are configured to engage and retain metal fasteners from the first side of the section of the recycled wood workpiece; and further comprising: a second stage supported by the chassis; and a second threaded fastener end effector: facing a second side orthogonal to the first side of the section of the recycled wood workpiece within the work volume; defining a second rotational axis; supported and manipulated on the chassis via the second stage; and comprising: a second ram configured to rotate about the second rotational axis of the second threaded end effector; a second ram actuator

configured to actuate the second ram; a second set of jaws coupled to the second ram and configured to engage and retract metal fasteners from the second side of the section of the recycled wood workpiece; and a second jaw actuator configured to actuate the second set of jaws.

14. The system of claim 13, wherein the controller is further configured to: access a second image of the work volume captured by the optical sensor; based on a second set of features detected in the second image: detect a second fastener in the second side of the section of the recycled wood workpiece occupying the work volume; and derive a second position and a second orientation of the second fastener in the work volume; define a second target engagement position of the second threaded fastener end effector, to engage the second fastener, based on the second position and the second orientation of the second fastener within the work volume; derive an extraction order for the first stage and the second stage based on the first engagement position and the second engagement position; trigger the second stage to drive the second threaded fastener end effector to the second target engagement position according to the extraction order; trigger the second jaw actuator to drive the second set of jaws to engage the second fastener in the second side of the section of the recycled wood workpiece; and trigger the second ram actuator to rotate the second ram and the second set of jaws about the second rotational axis of the second threaded fastener end effector to retract the second fastener from the second side of the section of the recycled wood workpiece.

15. A system for removing fasteners from a recycled wood workpiece comprising: a chassis: defining a work volume; comprising a set of lateral clamps configured to constrain lateral sides of the recycled wood workpiece at an input side of the chassis; and comprising a set of vertical clamps configured to constrain vertical sides of the recycled wood workpiece at the input side of the chassis; a conveyor: configured to receive the recycled wood workpiece populated with metal fasteners; and configured to constrain a section of the recycled wood workpiece within the work volume; an optical sensor facing the work volume; and a threaded fastener extractor module comprising: a stage supported by the chassis; and a threaded fastener end effector: supported and manipulated on the chassis via the stage; defining a rotational axis; and comprising: a ram configured to rotate about the rotational axis; a ram actuator configured to actuate the ram; a set of jaws coupled to the ram and configured to engage and retract metal fasteners from the section of the recycled wood workpiece; and a jaw actuator configured to open the set of jaws at a first height and to close the set of jaws to engage fasteners from the section of the recycled wood workpiece at a second height less than the first height.

16. A method for removing fasteners from a recycled wood workpiece comprising: receiving a section of the recycled wood workpiece within a work volume; accessing an image of the work volume, the image recorded by an optical sensor facing the work volume; extracting a set of features representing the section of the recycled wood workpiece from the image; based on the set of features: detecting a fastener embedded in the section of the recycled wood workpiece; and deriving a position and an orientation of a shank of the fastener; deriving a first target engagement position of a threaded fastener end effector, to engage the fastener, based on the position of the shank of the fastener; and in response to driving the threaded fastener end effector to the first target engagement position: locating the set of jaws within a threshold distance of the section of the recycled wood workpiece and spanning the shank of the fastener; driving the threaded fastener end effector to locate a rotational axis of the threaded fastener end effector coaxial with the orientation of the shank of the fastener; triggering a jaw actuator to drive the set of jaws into the section of the recycled wood workpiece and close the set of jaws to engage the shank of the fastener; and triggering a ram actuator to rotate the ram and the set of jaws about the rotational axis of the threaded fastener end effector to retract the first fastener from the section of the recycled wood workpiece.

17. The method of claim 16: wherein extracting the orientation of the shank of the fastener comprises extracting a breadth of the shank of the fastener based on the set of features; further comprising calculating a centroid of the shank of the fastener based on the breadth; wherein driving

the threaded fastener end effector comprises driving the threaded fastener end effector to align the rotational axis of the threaded fastener end effector coaxial with the centroid of the shank of the fastener; and further comprising triggering the jaw actuator to open the set of jaws by a distance proportional to the breadth of the shank of the fastener, in response to driving the threaded fastener end effector to the first target engagement position.

18. The method of claim 16: further comprising: accessing a three-dimensional model of the work volume occupied by the recycled wood workpiece labeled with fastener types, positions, and orientations; scanning the three-dimensional model for the fastener; and identifying the fastener in the three-dimensional model labeled with a screw fastener type based on the position and the orientation of the shank of the fastener; wherein detecting the fastener comprises detecting a screw embedded in the section of the recycled wood workpiece in the image; wherein extracting the orientation of the shank of the fastener comprises extracting the orientation of the shank of the screw; and wherein triggering the ram actuator comprises triggering the ram actuator to rotate the ram and the set of jaws about the rotational axis of the threaded fastener end effector to retract the screw from the section of the recycled wood workpiece.

19. The method of claim 16: wherein triggering the ram actuator comprises triggering the ram actuator to rotate the ram and the set of jaws about the rotational axis of the threaded fastener end effector to retract the fastener from the section of the recycled wood workpiece at a first time; and further comprising: recording a retraction force of the set of jaws, via a force sensor arranged on the set of jaws, at the first time; retracting the threaded fastener end effector from the first target engagement position to remove the first fastener from the section of the recycled wood workpiece at a second time succeeding the first time; recording a position of the threaded fastener end effector, via a position sensor arranged on the threaded fastener end effector, at the second time; and in response to the retraction force of the set of jaws falling below a retraction force threshold and in response to the position of the threaded fastener end effector falling within a target position range, identifying removal of the fastener from the section of the recycled wood workpiece at the second time.

20. The method of claim 16: further comprising defining a normal axis of the fastener relative a longitudinal axis of the section of the recycled wood workpiece based on the orientation of the shank of the fastener; and wherein driving the threaded fastener end effector comprises driving the threaded fastener end effector to locate the rotational axis of the threaded fastener end effector coaxial with the normal axis of the fastener, in response to driving the threaded fastener end effector to the first target engagement position.