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Application of a multi-head tool for robotic disassembly

Wei Hua Chen[a], Gwendolyn Foo[a,*], Sami Kara[a], Maurice Pagnucco[b]

[a] Sustainable Manufacturing and Life Cycle Engineering Research Group, School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney 2052, Australia
[b] School of Computer Science and Engineering, University of New South Wales, Sydney 2052, Australia

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ABSTRACT

The application of robotic disassembly or disassembly automation in industry is currently limited due to technological constraints on handling uncertainties in end-of-life product variation and condition. As a result, extensive research focuses on closing the gap between the need for robotic disassembly and the technological capabilities needed to deliver it. A multi-head tool utilizing a screwdriver, hole saw, and angle grinder has been developed and tested for the application of robotic disassembly of LCD screens. Each of the three tools is mounted on the wrist of an ABB IRB 140 industrial robot arm orthogonal to each other such that the robot need only rotate to apply a different tool head. The system builds upon a previous system which used only destructive and semi-destructive cutting methods, by introducing a force/torque sensor to guide force control for the non-destructive unscrewing skill and the less destructive drilling skill as options for the removal of screws. These alternative actions allow the system to deal with variations and unexpected outcomes of disassembly such as failures to disestablish a fastener with a particular skill, and if all alternative actions are exhausted, user demonstration is called upon.

1. Introduction

The fast-paced development and obsolescence of consumer electronics has led to concern for their end-of-life treatment. Disassembly allows the separation of components or material fractions from a product, allowing for potential component reuse, materials recovery, and proper treatment for hazardous components. Although disassembly automation is beginning to see an increase within large original equipment manufacturers (OEMs) (Tolio et al., 2017), a large proportion of electronics are still being treated at manual recycling facilities or processed abroad in less developed countries. Recyclers deal with products that arrive in varying conditions, unpredictable lot sizes of each product, and a general lack of product design and disassembly information. Hence, except for large-scale destructive methods such as shredding and crushing, the industry has generally preferred the flexibility of workers over the potential to automate disassembly.

1.1. Disassembly automation

Continued developments in robotics, disassembly tooling, and system design have the ability to increase the feasibility of robotic disassembly. The research in this paper was part of a larger project aimed at generic and robust disassembly that can be applied with little to no prior data regarding each product. The system operates based on product knowledge which can be generated during disassembly. For a system to be generic, the fundamental aspects of its operation should not be product specific. Such a system is built upon general techniques and knowledge, common among many product models and types. A system that is robust needs to be able to overcome uncertainties such as system inaccuracy and varying product conditions. A damaged component or fastener may not be separable using the preferred method. Hence, it is necessary to have alternative courses of action given the failure of the preferred technique or plan. These concepts were applied to a disassembly system for liquid crystal display (LCD) screens.

1.2. Disassembly tooling

While non-destructive disassembly is preferable to preserve the embodied energy of components, this tends to require more specialized tools and is more prone to error since they rely on the

* Corresponding author.
E-mail address: gwendolyn.foo@student.unsw.edu.au (G. Foo).

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integrity of part shapes and surfaces. On the other hand, semi-destructive actions are more versatile and robust (Uhlmann et al., 2005). A circular cutter is typically able to cut through any fastener, even if the fastener itself is unrecognized by the system. Semi-destructive disassembly may involve damage to fasteners but not main components.

A specialized bit was designed for the removal of screws irrespective of head shape, by generating new acting surface shapes for unscrewing (Feldmann et al., 1999). Another flexible unscrewing tool operates by creating new acting surfaces using wedges and high frequency impacts (Rebafka et al., 2001). An obsolete wave soldering machine was reworked in Palmieri et al. (2018) and Marconi et al. (2018) to de-solder printed circuit boards (PCBs). Figueiredo (Figueiredo, 2018) focused on the design of a scoop tool for prying apart cellphones. In destructive disassembly, using only an angle grinder mounted to a robot, LCD screens were separated to module level components, although not without damage and contamination (S. Vongbunyong et al., 2013). Cutting blades, air blowers, scrapers, drills, and even a fiber laser station was implemented in Wang (Wang, 2017).

A mix of tooling is desirable to allow the system to take advantage of the benefits of both destructive and non-destructive techniques. For this work, a screwdriver, drilling tool and angle grinder have been shown to be adequate for separating fasteners in an LCD screen for destructive disassembly. This work investigates the tool design option to simultaneously affix all three tools to the robot wrist at different axes, eliminating the need for an external system for tool change.

1.3. Advanced disassembly tooling

Where uncertainties in the state of the world are significant, sensor input can be used. However, the accuracy of sensors may not be sufficient for all disassembly tools and skills. Wang (Wang, 2017) addressed this by mounting an intelligent camera and light source on the end of a robot arm in order to get closer and more accurate views of screw centres. A searching motion skill was implemented with a pneumatic tool for robotic unscrewing (Alici, 1999), compensating for system inaccuracy. Cruz-Cruz-Ramírez et al. (2011) demonstrated the ability to remove a screw from a rail using sensed forces despite inaccurate model information. Low cost pressure sensors have also been an aid in the removal of snap-fit battery covers (Schumacher and Jouaneh, 2014). In many of these cases, tactile strategies were employed to overcome sensor inaccuracies.

Discrete-continuous control is a concept where trajectory and continuous control are handled solely within primitives, whereas each primitive is a discrete state in a Petri net (G. Milighetti and Kuntze, 2006; Milighetti et al., 2005; G. Milighetti and Kuntze, 2006). This architecture is supportive of learning and error handling, both of which are desirable in the disassembly application. A similar discrete-continuous architecture has been adopted in this project. Each action or skill is implemented as a finite state machine. At each state, the control function simultaneously defines the robot's behavior and performs execution monitoring. Detectable errors or unexpected deviations from normal execution can lead the program into alternative routines for learning or error recovery. The initial trial using this architecture was presented in Chen et al. (2014). The concept of describing a disassembly action using well-defined states and transitions was also used in Schumacher and Jouaneh (2014).

2. System overview

Fig. 1 shows the physical configuration of the robot rig and tooling. The robot manipulator is an ABB IRB140 robot arm driven by

Fig. 1. Multi-head tool mounted on robot.

an IRC5 Robot Controller. Two high-torque 12 V DC motors were mounted in opposite directions, one driving a Phillips #2 screwdriver bit, and the other, a keyless chuck, to which various drill bits could be attached. Manual disassembly of samples suggested that the Phillips #2 screwdriver was sufficient to disassemble almost all LCD screens to the module level. A Makita 840 W angle grinder was mounted with the blade orthogonal to the drill and screwdriver axes. These tools were fixed to the robot wrist via a JR3 67M25 6-axis force/torque sensor. A small outlet of compressed air is directed to the cutting blade to blow away chips and swarf from cutting and prevent the tool from jamming.

LCD screens are fixed to a flipping table - a platform attached to a shaft driven by a 180 V DC motor. As in S. Vongbunyong et al. (2013), the flipping table flips the product such that components which have been completely detached from the fixed subassembly fall out by virtue of gravity. This method of component separation means that the challenge of gripping complex and differently shaped objects is bypassed. The product is held in position via the vacuum grippers located at the center of the flipping table and can be positioned to within 0.5 mm accuracy. The vision system consists of a Microsoft Kinect v1 for Xbox 360 depth camera, a 1-megapixel IMPERX IPX-1M48-L color camera, and ambient room lighting.

The robot controller is programmed using the RAPID programming language and runs two tasks in continuous cycle: a motion task and a monitoring task. The computer continually monitors and records the robot's path during motion and interrupts the robot's motion when necessary. Additionally, the monitoring task automatically handles collision-related errors, causing the motion task to restart and send an appropriate error message to the computer.

3. Multi-head tool

All cutting, drilling and unscrewing actions are assumed to be made with the tool perpendicular to the working surface. The fact that the grinder blade can be rotated 180° to produce the same cut is used as a choice point in the program if a collision is detected. In many cases, this alternative position is collision-free. To simplify the motion planning problem, discrete possibilities for tool orientation are manually selected and each configuration saved.

Tool calibration is performed by manually jogging the robot such that the tooltip is at the global origin $(0,0,0)^T$ and the tool is

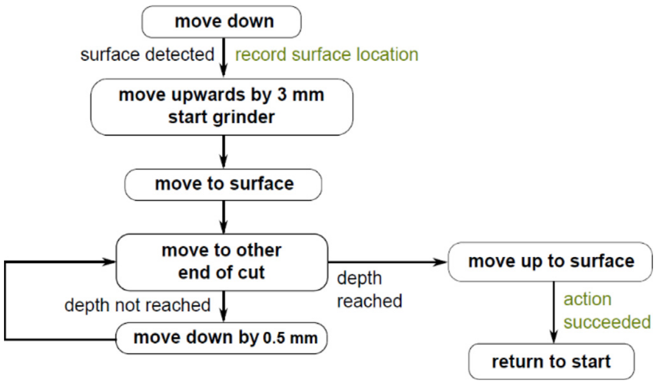

Fig. 2. Basic cutting procedure.

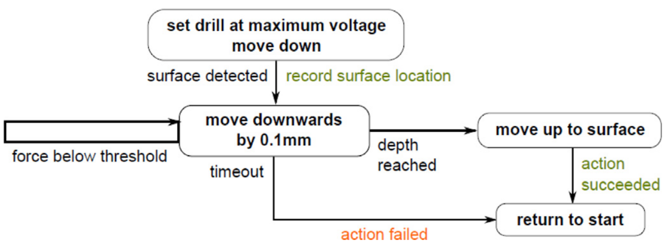

Fig. 3. Drilling state diagram.

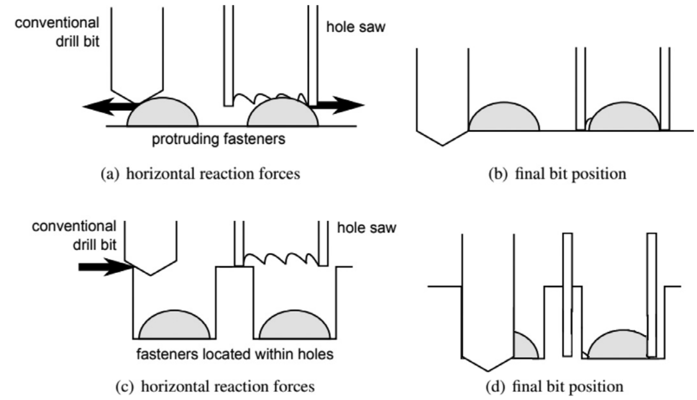

Fig. 4. Effect of small positioning errors while drilling.

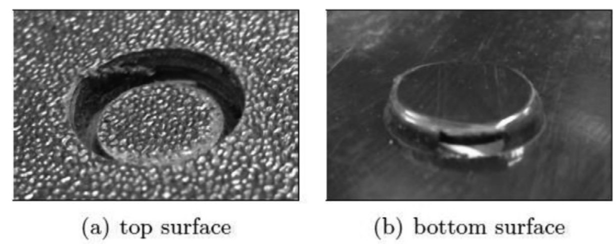

Fig. 5. False positive detection (incomplete separation) due to plastic deformation.

in alignment with features on the rig. The global origin was fixed at a physically drawn point on the flipping table.

In order for the robot to change tools without colliding with itself or re-wrapping its cables in an undesirable way, a home position was manually defined where the robot wrist is able to freely rotate without colliding with the rig.

The following sections describe the methodology taken for implementing each of the skills of cutting, drilling and unscrewing for the robot system.

3.1. Cutting

The procedure used for cutting a line using the angle grinder is described in Fig. 2. A cut to a particular depth is performed by incrementally increasing the depth of cut starting from the surface. This was envisaged to cause less heat generation than a single-pass strategy by spreading the material removal rate over a greater area. Diamond blades were used over steel grade and multi-material grade abrasive discs due to their low wear rate. A default depth increment of 0.5 mm and a feed rate of 25 mm/s is implemented.

3.2. Drilling

Drilling can remove point fasteners such as screws and rivets with less destruction than cutting. In conventional machine drilling, correct contact forces are generated by controlling the feed rate in conjunction with high rigidity and a powerful drive system. Alici (1999) identified the need to directly control axial force, as robot manipulators are not sufficiently rigid and carry limited power. A force/torque sensor is mounted between the robot and tool for force feedback. The proposed control method involved an inner position control loop, nested inside an outer loop that specifies desired changes in position to maintain the desired force.

The drilling skill is described in Fig. 3. The force threshold for surface detection was set to the desired drilling force, to account for the displacement of the component due to bending. If, after a given period of time, the force has not dropped below this threshold, the drilling action is considered unsuccessful. In this case, we deem that the robot is unable to drill through the material. Once this occurs, or the drilling operation is completed, the robot moves back to the starting location, then turns off the drill.

3.2.1. Hole saw

It was observed that a conventional drill bit was not effective in removing fasteners as the tool would deflect significantly when landing on a convex surface such as a screw head (Fig. 4). Screw head hardness also made it difficult to drill through. Therefore, a hole saw was utilized to cut around fasteners instead. A Lenox 16 mm bi-metal hole saw was used.

3.2.2. Drilling force

Insufficient drilling force can result in incomplete separation due to plastic deformation and false positive detections of drilling success by the robot (Fig. 5). A feasible drilling force of 50 N was selected from drilling experiments on a variety of materials and thicknesses (Chen, 2017), allowing the action to be determined as failed if the blade does not cut properly or the material is too hard.

3.3. Unscrewing

3.3.1. Screw engagement

This work used only detected forces to discern screw engagement. A minimum initial axial force of 5 N was applied to the workpiece and the robot moved downwards by 0.2 mm increments. Screw engagement is identified when a threshold reaction force of 50 N is detected, as this sudden and significant increase in axial force caused by the screw's head pushing on the screwdriver, meaning that the screwdriver is engaged with the screw head (Fig. 6).

Nave (2003) employed a spiral shape searching motion for the screwdriver to find the screw head. This concept was implemented and combined with proportional force controls in the x and y directions, and axial force control as previously described, to move the screwdriver in a local searching motion while slowly lowering

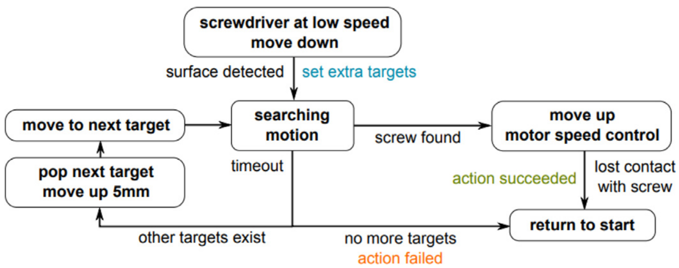

Fig. 6. Unscrewing state diagram.

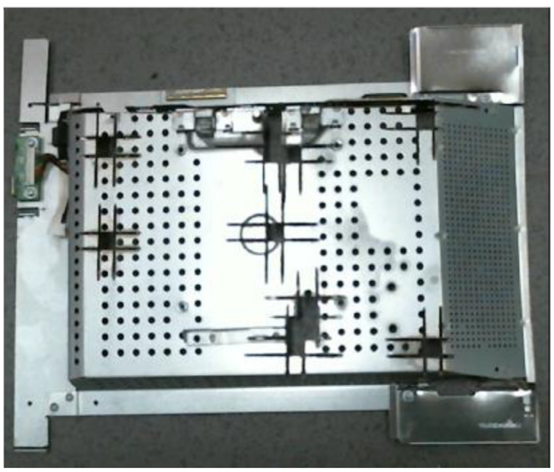

Fig. 7. Cut steel cover of an LCD screen.

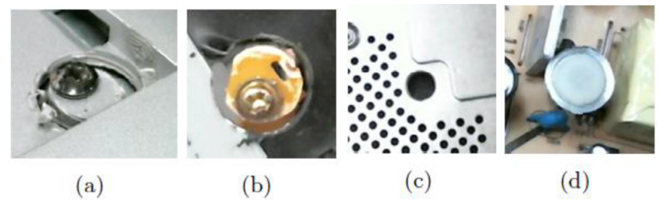

Fig. 8. Examples of drilling/hole cutting in the disassembly of LCD screens.

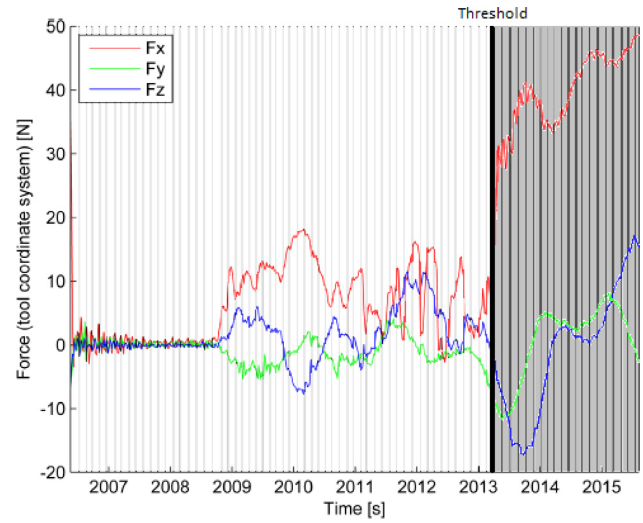

Fig. 9. Forces during searching motion.

downwards according to the contour of the workpiece until reaching the local minima. This is programmed to time out if screw engagement is not detected within 12 s.

In an attempt to increase the search area and hence the success of finding the screw head, the spiral searching motion was implemented to be repeated four additional times: above, below, and to the left and right of the expected location. Each of these additional points are searched, if the first attempt fails to find a screw head.

3.3.2. Unscrewing and bit removal

After screw engagement is detected, unscrewing involves accommodating for screws with different and unknown pitch in order to reduce the chances of losing contact with the screw prematurely. This is done by controlling the motor and robot speed according to sensed forces. This motion state is programmed to terminate if the sensed force remains under a threshold of 2 N for more than 1 s, indicating that the robot has lost contact with the screw.

Due to the magnetic nature of the screwdriver used, removed screws occasionally remained attached to the screwdriver bit. A mechanical piece was designed for the removal of a screw from the bit, using a similar principle to the disengagement of the socket wrench bit in Chen et al. (2014). This was written as a procedure separate from the unscrewing skill.

4. Results

4.1. Cutting

During removal of screws by cutting, an added ability to sense the location of an unknown surface (Fig. 7) led to less damage to the cutting blade than compared to Vongbunyong (2013).

4.2. Drilling

Successful drilling of fasteners to separate components are shown in Fig. 8. (a) and (b). Drilling of flat surface plastics and PCB substrate material are successful in every observed instance. Fig. 8. (d) shows the clip, located within a chamfered hole in the steel cover, separated from (c) where the hole saw was able to cut through steel, although it was not always successful. Unsuccessful drilling may occur due to material hardness, tool bluntness, slipping, or stalling of the drill. Stalling tended to occur when drilling metal of complex geometry such as steel covers with holes.

4.3. Unscrewing

The system was used to remove screws from the back cover of five screens and the inner components of three screens. Manual observation formed a truth tally regarding the correct engagement of screws. The results from a total of 52 unscrewing attempts are shown in Table 1.

Screws engaged refers to the percentage of screws for which engagement with the screwdriver tool tip was detected, by the procedure in 3.3 Unscrewing. Recall is defined as the percentage of the screws that were actually successfully engaged, out of the screws detected as engaged. The success rate is the percentage of instances that screw engagement was both detected by the system and the case in reality. The success rate was lower than desired, largely due to the low percentage of screws engaged and the low recall on inner components. Low screw engagement can be attributed to the error in the vision system and robot positioning.

Half of the total of 34 extracted screws were engaged during the first application of the searching motion. The strategy of attempting 4 additional targets was able to double the rate of screw engagement at the expense of increased time.

Table 1
Unscrewing results.

Object type	Screws engaged [%]	Recall (detection) [%]	Success rate [%]
Back covers	71.4	90.0	64.3
Inner components	58.3	42.9	25
Total	65.4	70.6	46.2

Fig. 9 shows the forces sensed during searching for the screw head. The thick vertical line represents detected screw engagement from the threshold axial force of 50 N onward. Contact forces remain bounded between −10 N and 20 N prior to rapidly increasing, suggesting screw engagement.

5. Discussion and future research

5.1. Discussion

In the larger proof-of-concept system, the appropriate cutting and drilling depths were generally unknown before the completion of an operation. Therefore, to facilitate system integration, the capacity to accept user demonstration during operations was also added to the cutting and drilling skills.

The results show that the robot system could perform the skills of cutting using an angle grinder, drilling, and unscrewing on workpieces where the material and exact fastener characteristics are unknown. This is, overall, sufficient for integration into a proof-of-concept system aimed at the disassembly of LCD screens with little product foreknowledge. Aside from the flipping table, these are the sole actions used by this system to separate connections of LCD screens. The ability to unscrew, drill, and cut, allowed this system to disassemble PCBs with significantly less damage than only using cutting methods as per the previous system (Vongbunyong, 2013). However, user intervention is still required to supply necessary information such as an accurate screw location and the desired cutting depth.

The challenge of determining cutting depth was addressed by using sound and visual feedback as well as background knowledge regarding the expected shape of the components and user input. This enabled successful execution of cutting actions without prior knowledge of specific product structure and model components.

From disassembling LCD screens with this developed system, it was evident that the melting of plastic was more problematic at the intersection of cuts, where melted plastic from the second cut would fill the volume within the initial cut. This could prevent the relevant components from detaching and falling away upon flipping of the table. This side effect of cutting was able to be reduced by switching from a 1.15 mm diamond blade to a 2 mm diamond blade, however it did not completely solve the issue. The toothed tungsten carbide-tipped blade was found to result in significantly less plastic melting but is unsuitable for cutting steel, causing significant vibrations and high wear rates. The search for an effective cutting tool for a variety of materials remains open.

It was observed that the addition of proportional control based on sensed forces to the spiral searching motion for screw engagement, especially where the tool is moving over complex geometries, caused non-zero forces to be sensed in the transverse directions. This stops the robot from sweeping an area which would otherwise be searched. Additionally, due to the curvature of the workpiece and rotation of the screwdriver, the robot strayed significant distances from the starting search location, disabling the robot from finding the screw, even if it was within the 1.5 mm vicinity. Therefore, the absence of force control in these directions can result in high forces and hence false positive detections of screw engagement.

The detection of screw engagement was affected by the stiffness of the system and workpiece. A highly flexible workpiece may deflect without applying sufficient force on the robot to trigger screw engagement detection, resulting in false negative detections. This is currently solved by user intervention. To reduce this, a future implementation for screw engagement detection based on time rather than force may be feasible.

5.2. Future research

Different possibilities for future extension of this work exist. Aside from optimizing the individual skills, through improved hardware, control strategies or automated parameter learning, the disassembly process can be optimized via further investigation into motion planning. A motion planner can also potentially allow a robot to directly move from one skill application to another and perform skills in a sequence that further optimizes disassembly time. The initial observations and insights are useful for the future development of disassembly systems; particularly those aimed at being robust to product variation and the failure of non-destructive operations.

6. Conclusion

A disassembly system requires the ability to remove fasteners and separate connections between components. For the disassembly system, skills were required that could remove fasteners in a wide variety of product models. This system was set up with a robotic tool holding a screwdriver, drill, and angle grinder, with each active tooltip in directions orthogonal to each other. The methodology for the control of this system to achieve the skills of cutting, drilling and unscrewing was described in this paper. The results of applying these skills to real products (LCD screens) and the knowledge gained through the development, implementation and testing of these skills have been further presented. One advantage of the integrated tool design is that the robot is not required to travel to a particular location for tool change. This paper provided procedures for movement and tool change adequate for this proof-of-concept system which increased the system's flexibility in executing non-, semi-, and fully destructive operations while minimizing time required.

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