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Gormley et al.

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(54) **MANUFACTURING WOVEN TEXTILE PRODUCTS**

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D03D 37/00 (2006.01)
D03C 3/20 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***D03D 37/00*** (2013.01); ***D03C 3/205*** (2013.01); ***D03D 3/02*** (2013.01); *D10B 2403/0333* (2013.01)

(58) **Field of Classification Search**
CPC D03D 37/00; D03D 3/02; D03C 3/205; D10B 2403/0333
See application file for complete search history.

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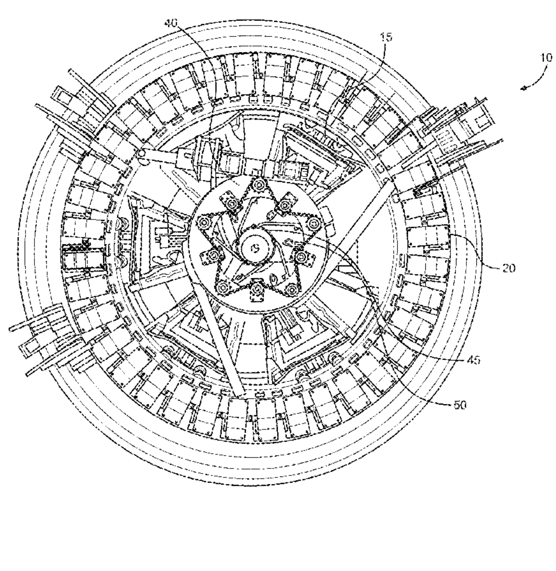
(57) **ABSTRACT**

A circular loom for continuously weaving fabric with a varying diameter includes a variable diameter weaving ring, independently actuated heddles, and at least one shuttle including a weft insertion arm attached to a linear rail system configured to adjust the position of weft insertion arm based on a diameter of weaving ring. An associated method includes varying the diameter of weaving ring, indepen-
(Continued)



dently actuating heddles and adjusting the position of weft insertion arm along linear rail system to continuously produce hollow textile products having variable diameters.

23 Claims, 14 Drawing Sheets

(51) **Int. Cl.**

D03D 3/02	(2006.01)
D03D 49/00	(2006.01)

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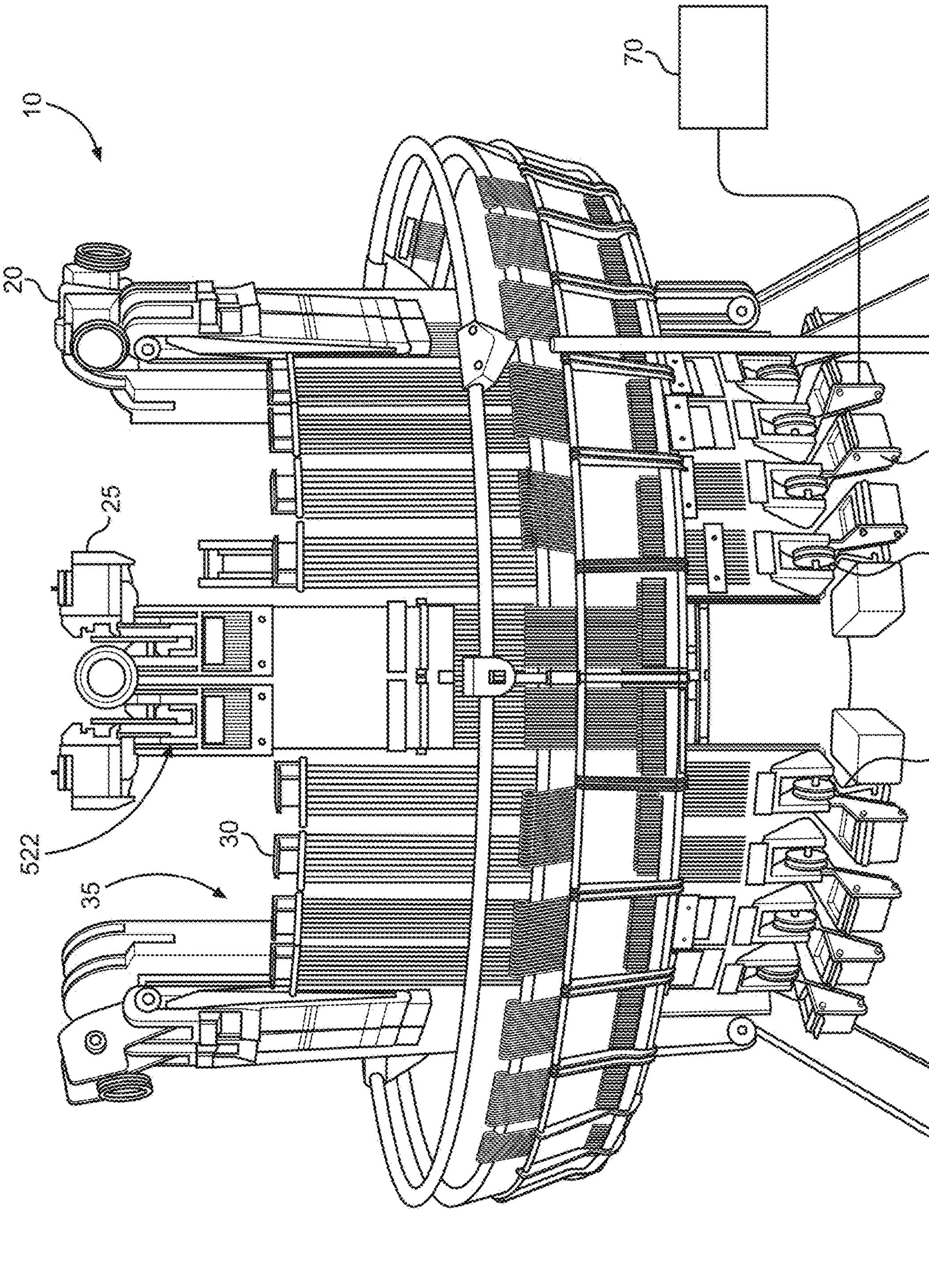

FIG.1

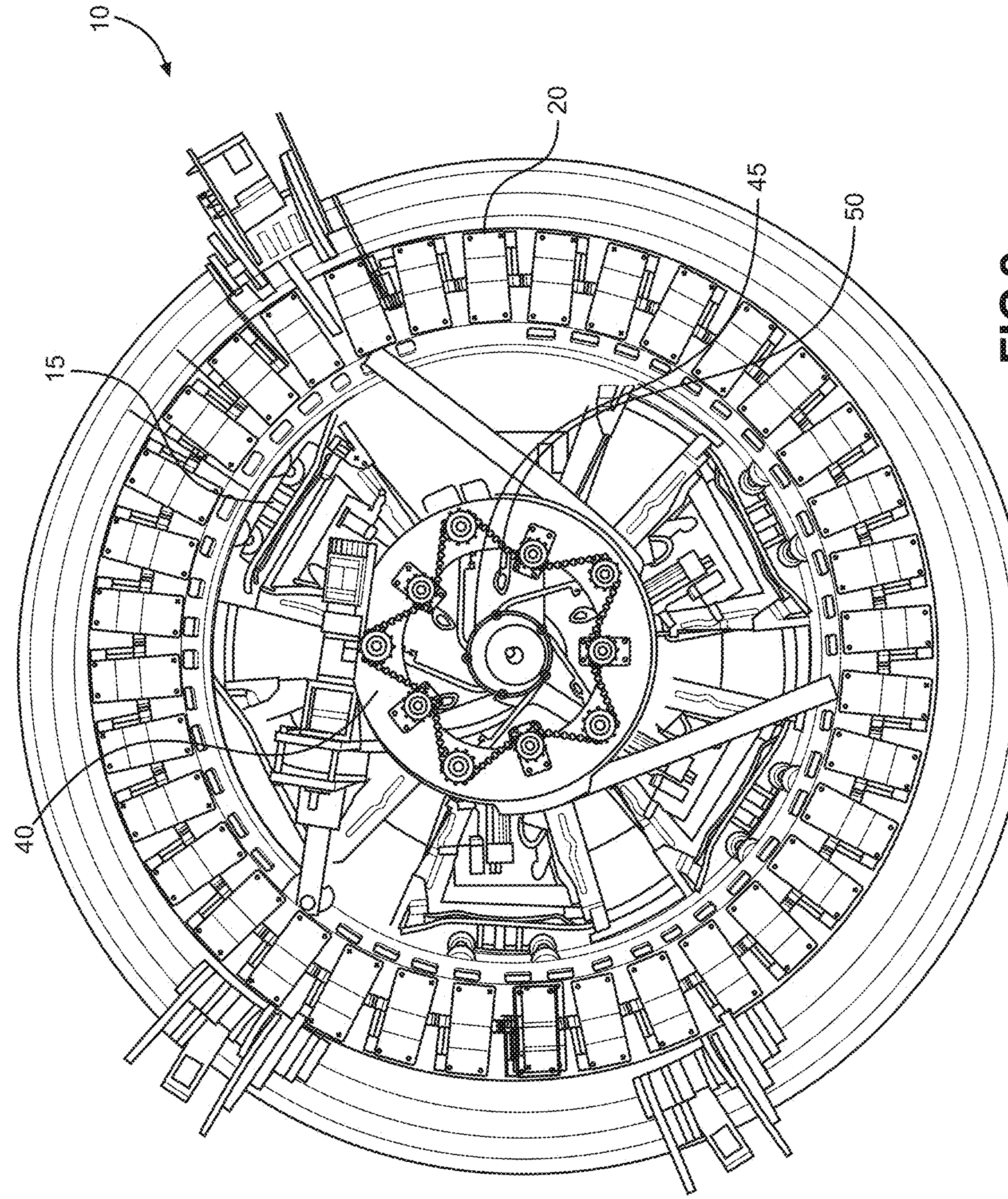

FIG.2

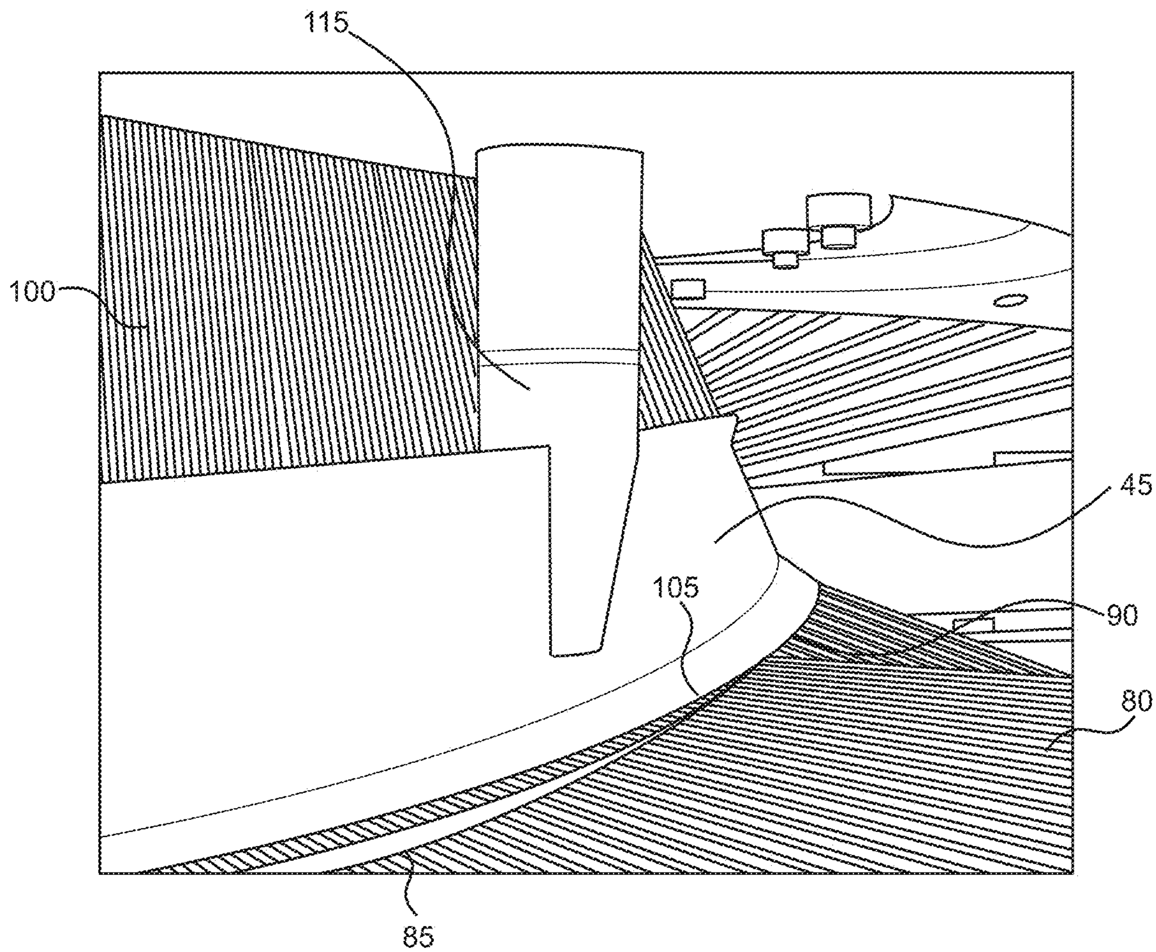

FIG.3

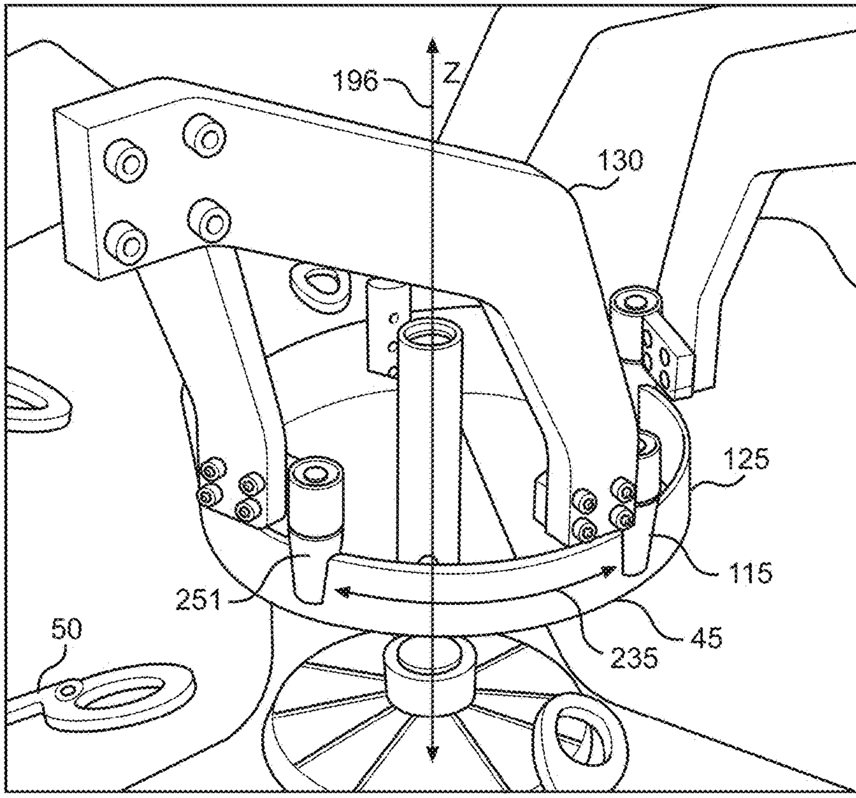
196
Z
130
120
125
115
251
50
235
45

FIG. 4

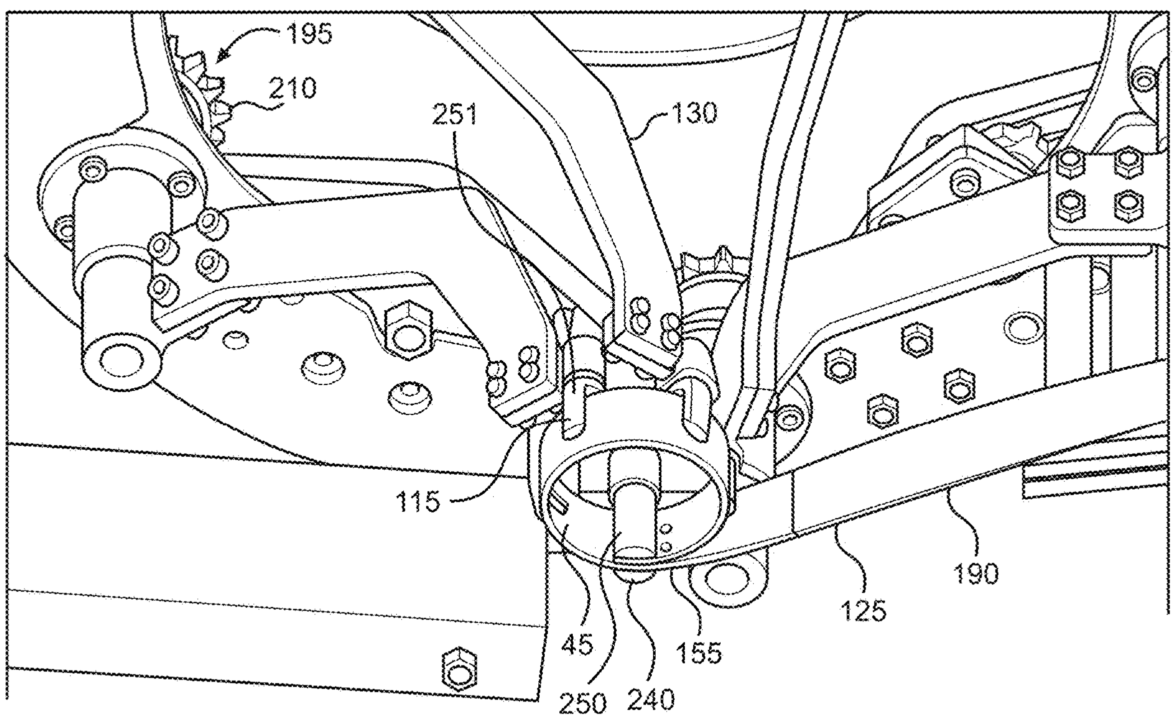
195
210
251
130
115
190
125
45
155
250
240

FIG. 5

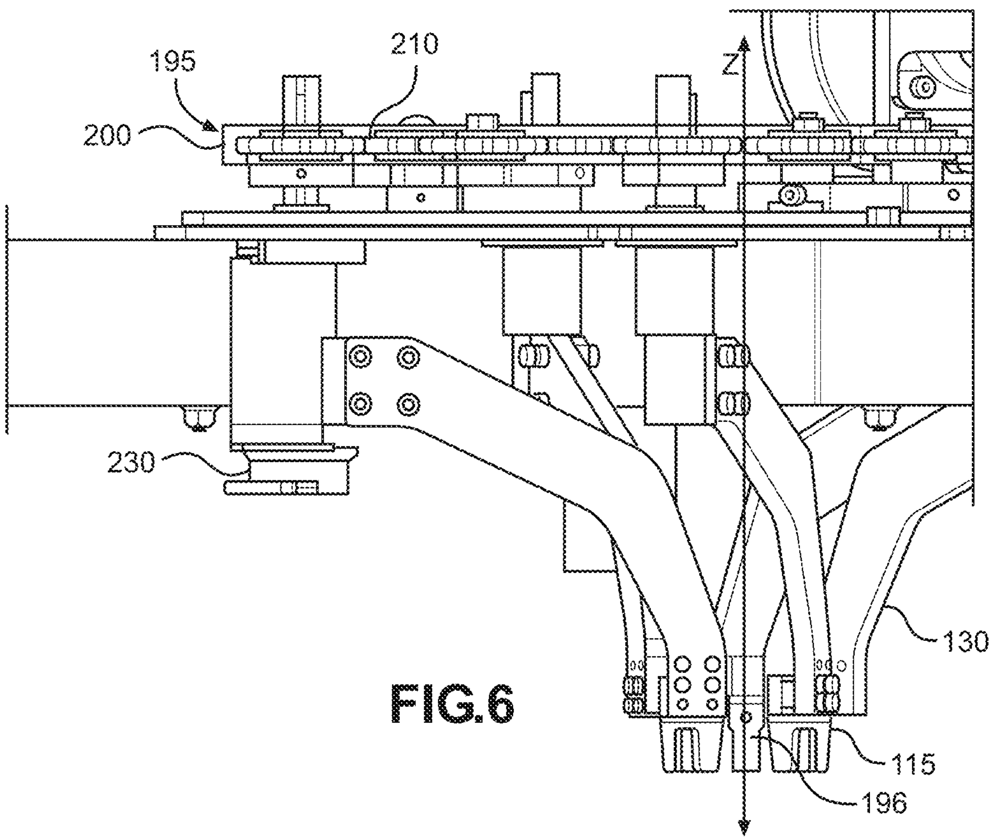

FIG.6

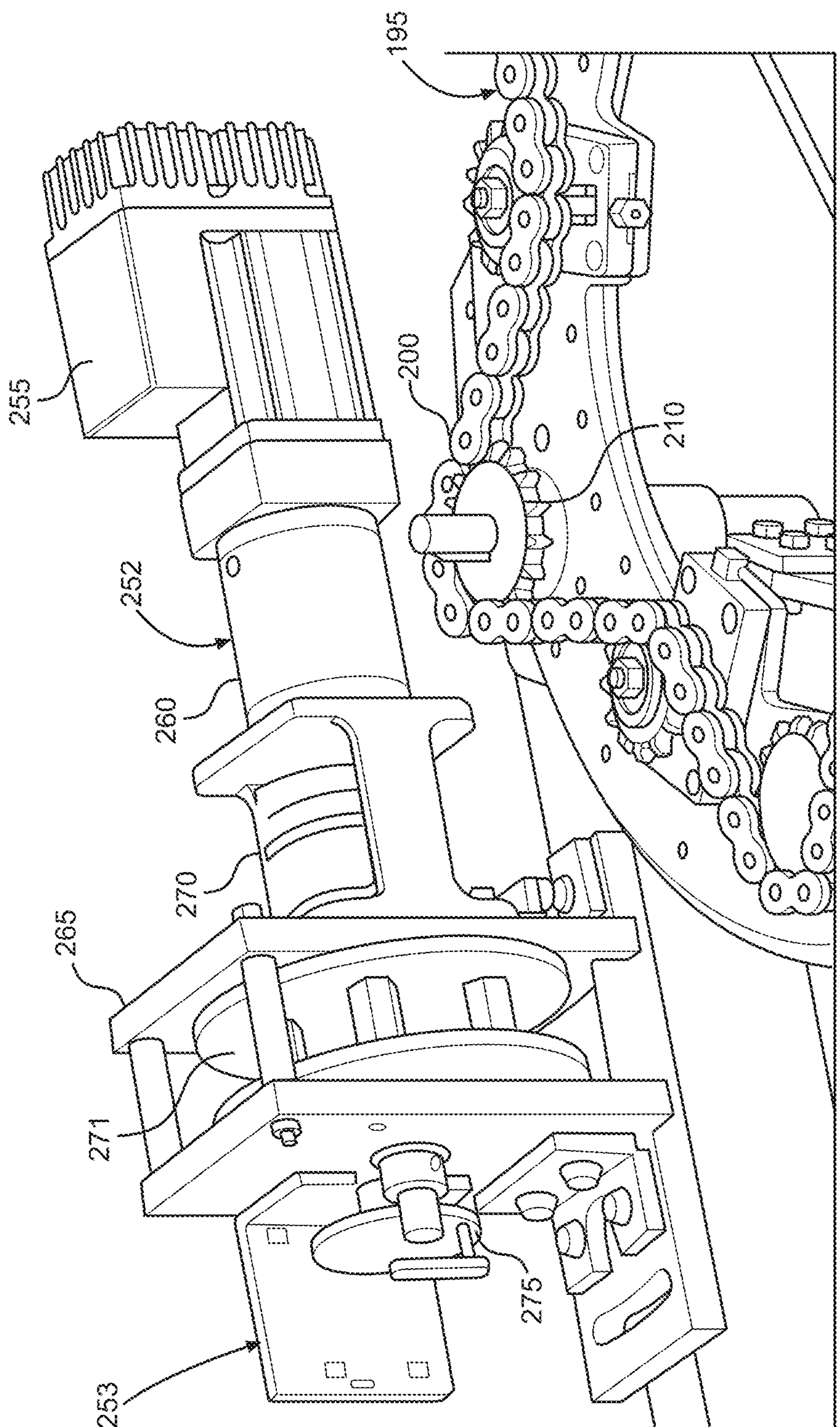

FIG. 7

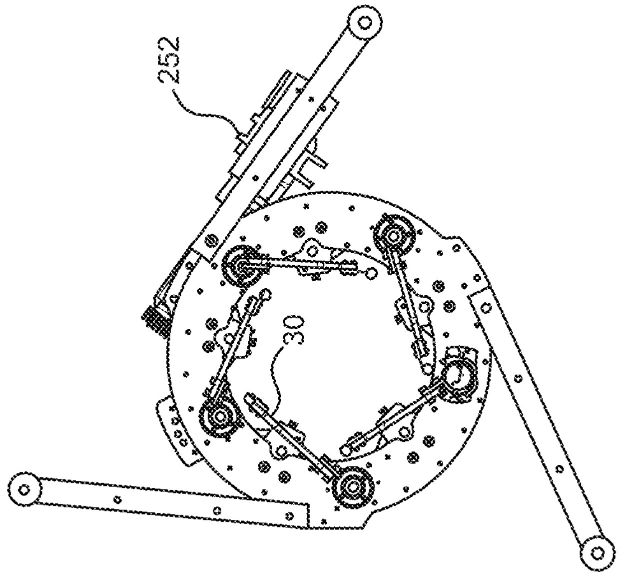

FIG.10

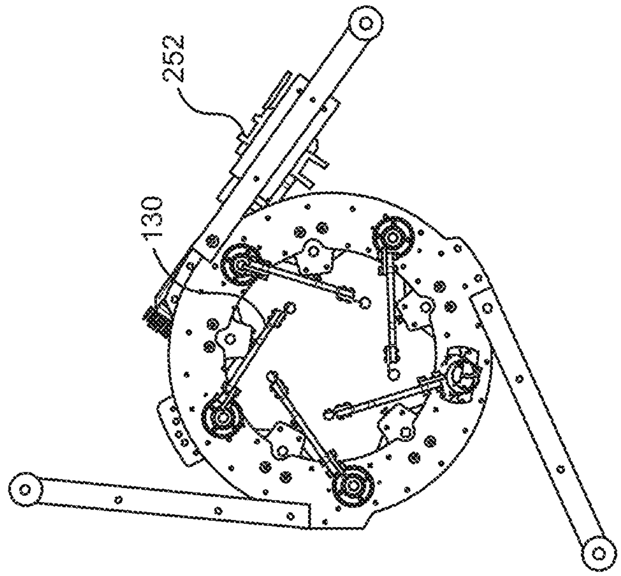

FIG. 9

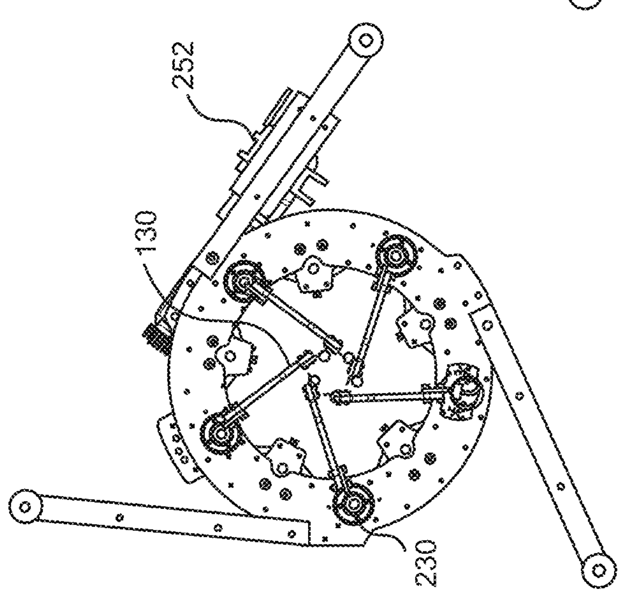

FIG. 8

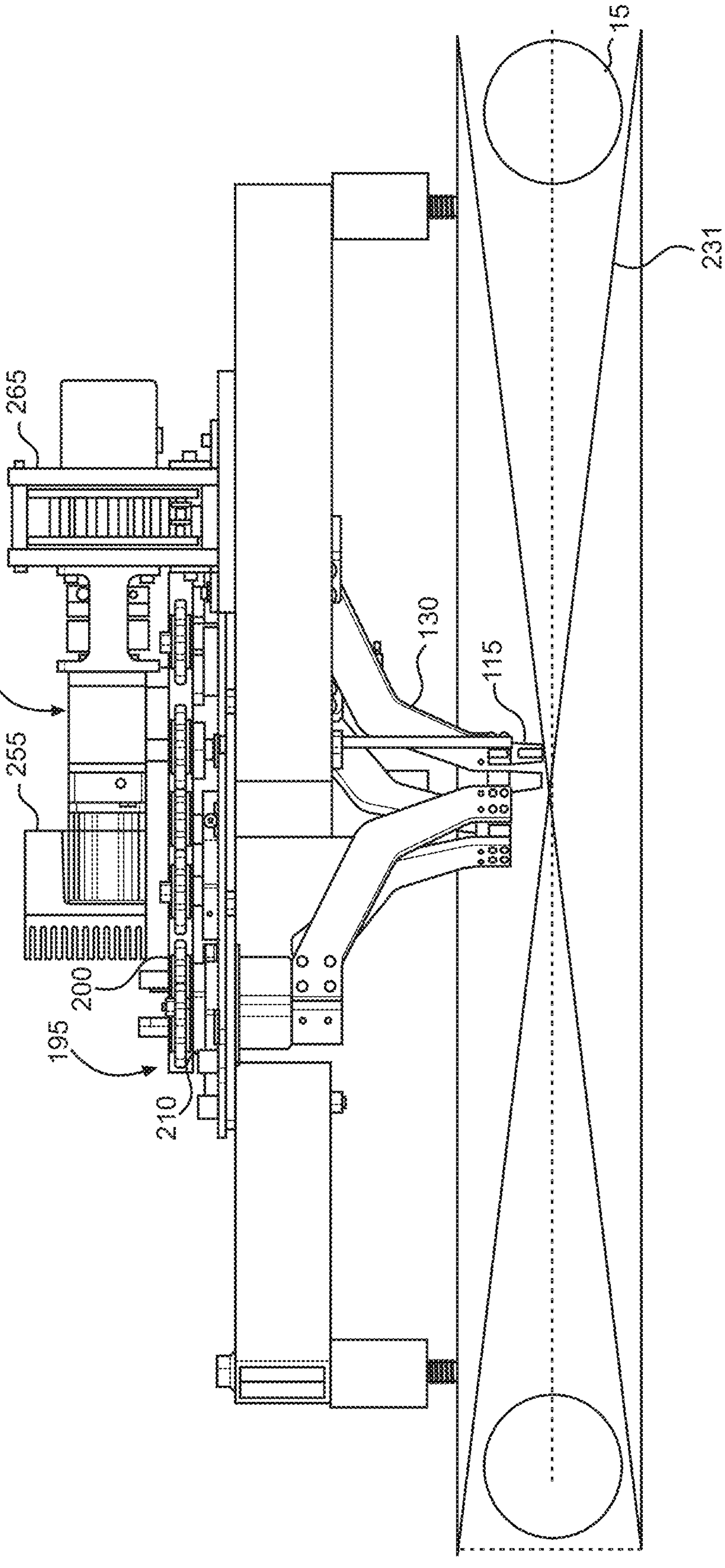

FIG.11

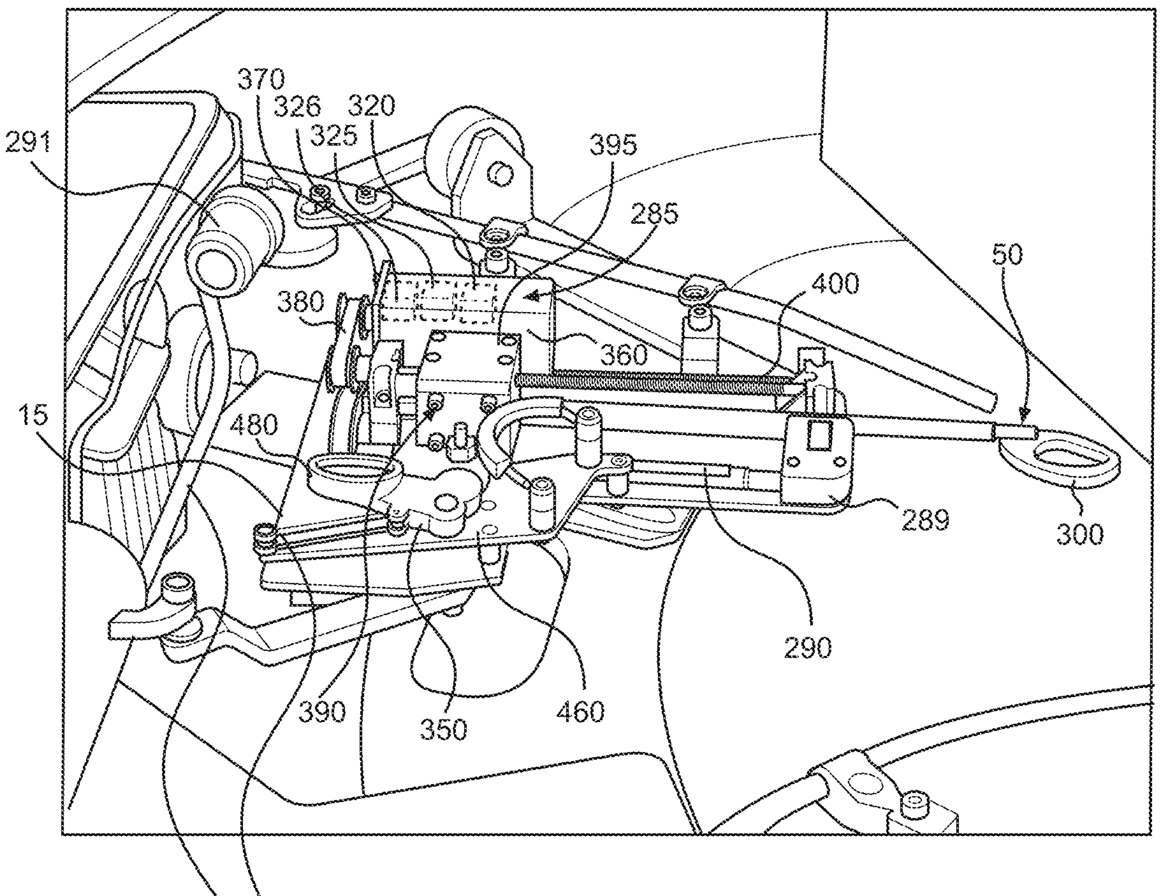
370
326
320
325
291
395
285
50
400
380
360
15
480
289
300
290
390
350
460
475
481

FIG. 12

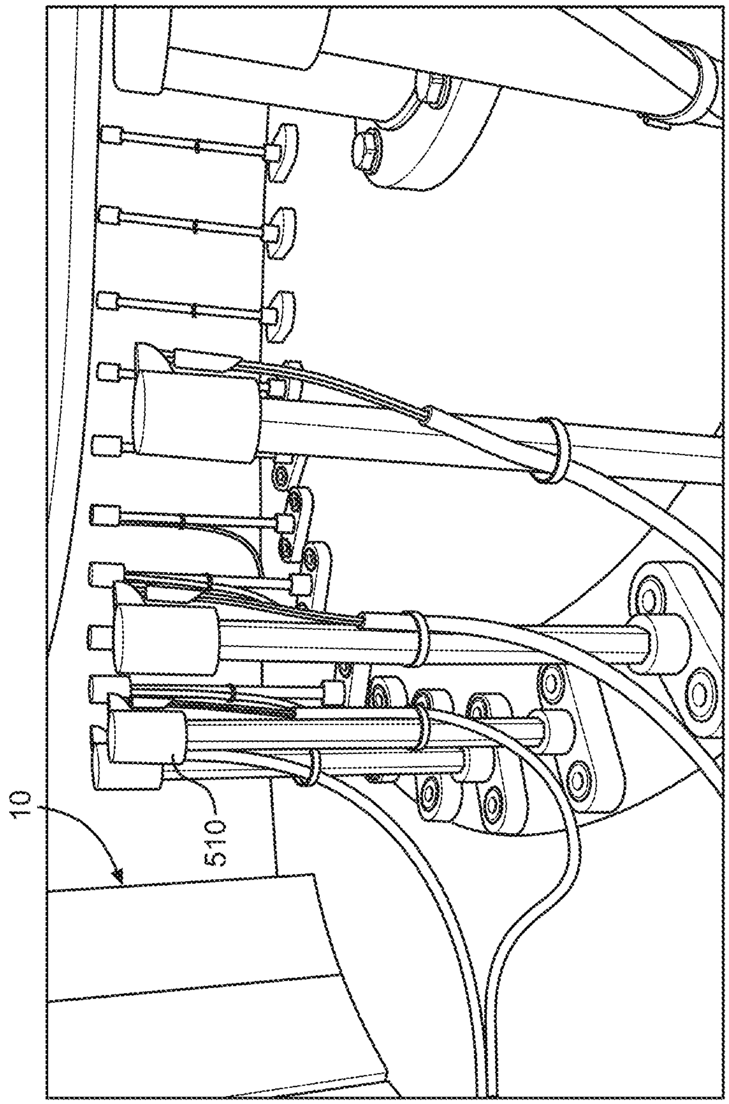

FIG. 14

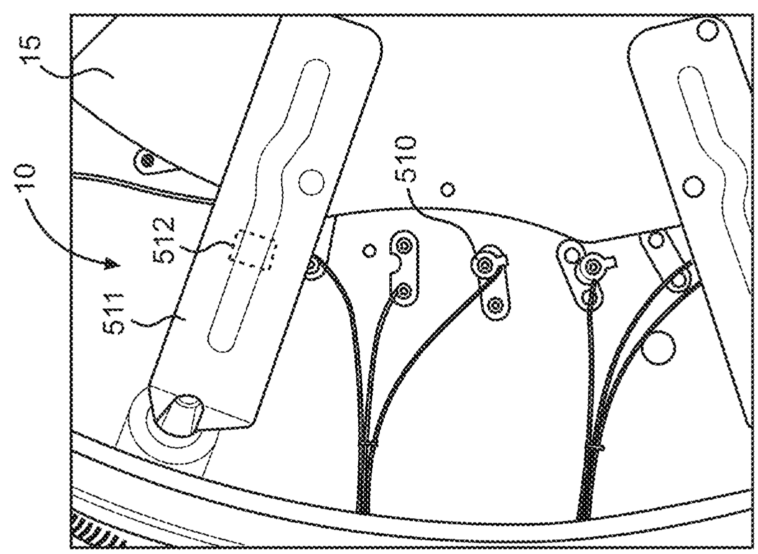

FIG.13

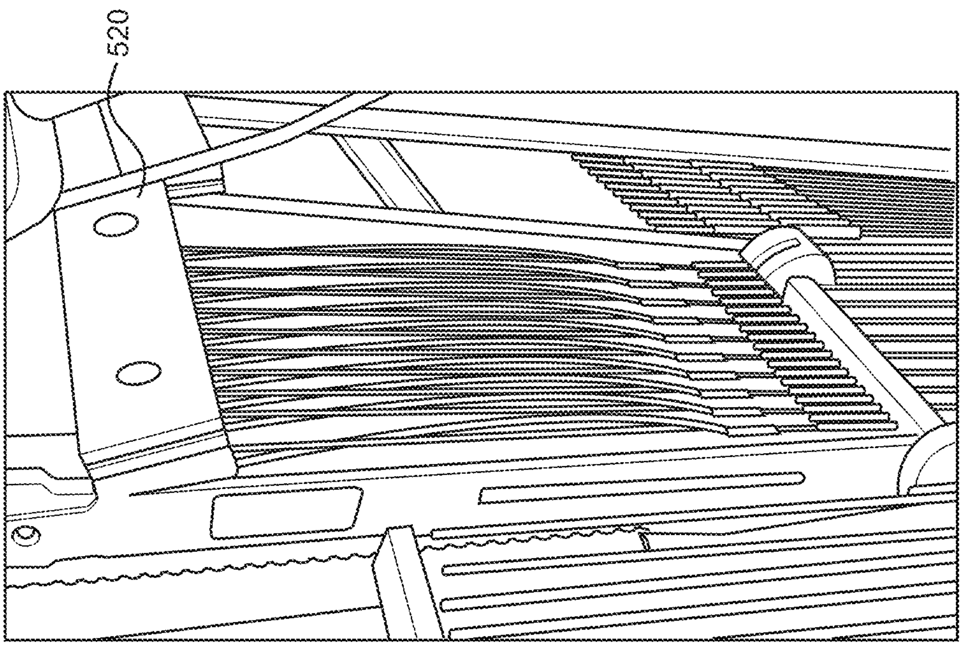

FIG. 16

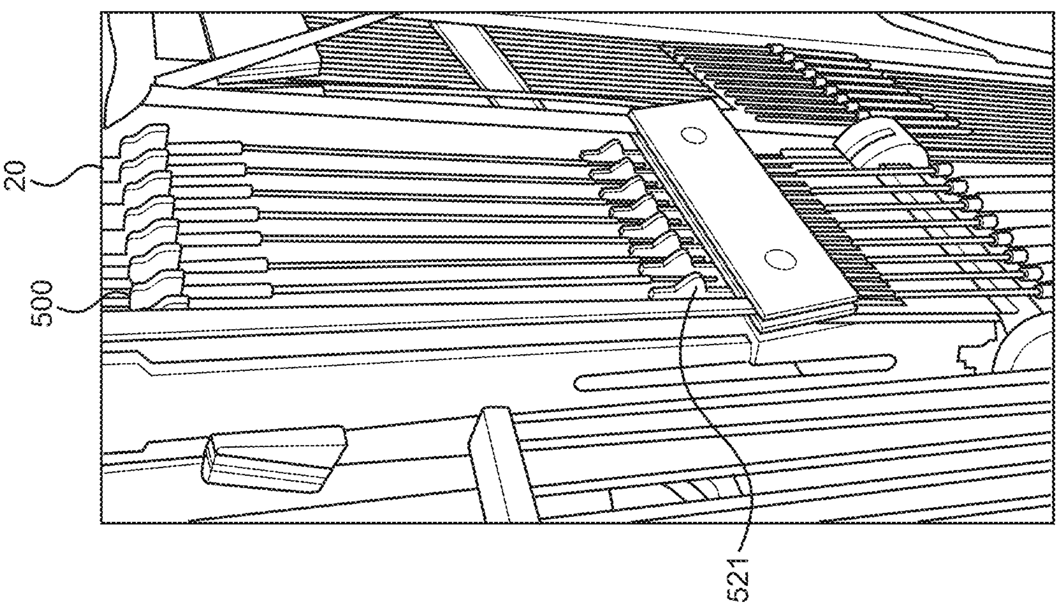

FIG. 15

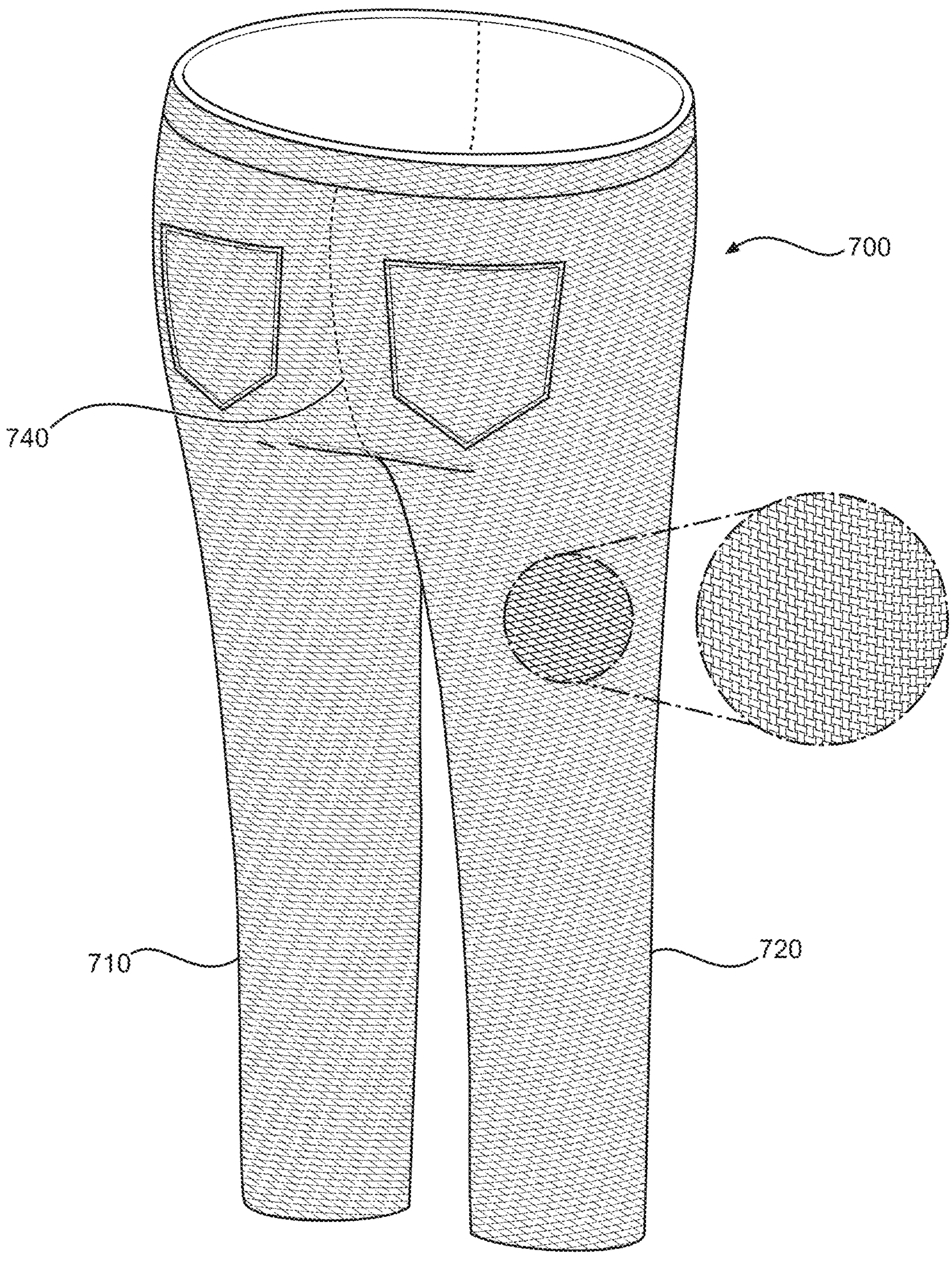

FIG. 17

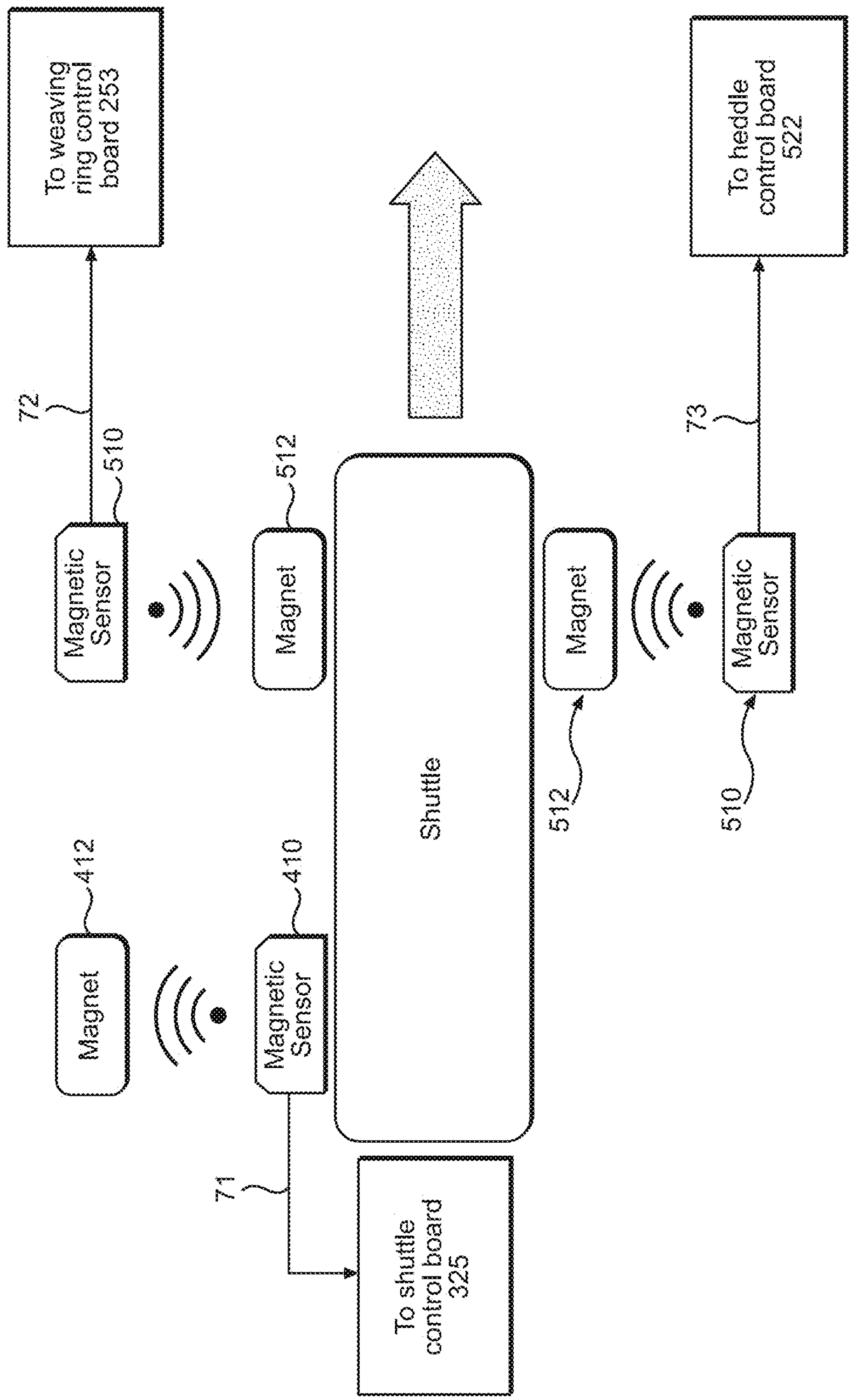
To weaving ring control board 253
72
510
Magnetic Sensor
512
Magnet
To heddle control board 522
73
Magnet
Magnetic Sensor
512
510
Shuttle
412
Magnet
410
Magnetic Sensor
71
To shuttle control board 325

FIG. 18

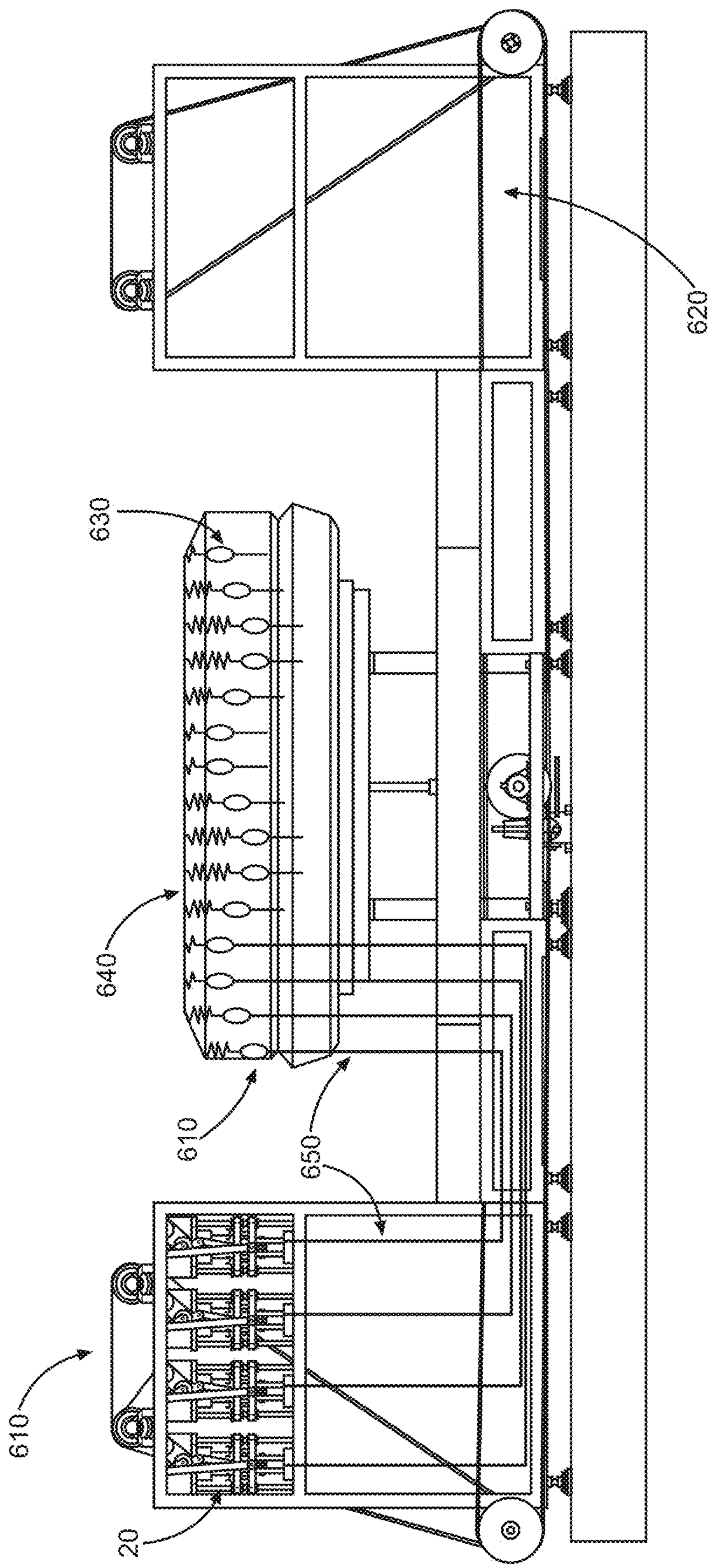

FIG. 19

MANUFACTURING WOVEN TEXTILE PRODUCTS

CROSS REFERENCE TO RELATED APPLICATIONS

This application represents the U.S. National Phase of International Application number PCT/US2023/011970 titled "Manufacturing Woven Textile Products" filed on Jan. 31, 2023, which claims the benefit of U.S. Provisional Application No. 63/304,944 titled "Manufacturing Woven Textile Products" and filed on Jan. 31, 2022, which is incorporated herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under Grant Number 1831088 awarded by National Science Foundation. The government has certain rights in the invention.

TECHNICAL FIELD

The present invention is in the technical field of manufacturing woven textile products and, more particularly, to circular looms for weaving hollow textile products such as articles of clothing.

BACKGROUND

The production of textiles and garments has changed little over time. Garments are generally produced in mass quantities, stored in warehouses and then transported to clothing stores for display. Numerous different sizes of each type of garments have to be stored and displayed to fit the different sizes of the various people shopping in the clothing stores. Clothing manufacturers and sellers simply estimate how many articles of each size of clothing will be sold and produce that amount of clothing. Storage of clothing has an associated cost and when manufacturers produce the wrong amount of clothing, sales are lost due to a lack of desirable sizes of clothing and excess inventory of clothing may remain unsold. Excess inventory is often discarded in landfills or incinerated, creating substantial environmental harms.

Woven textiles have several advantages over knitted textiles. For example, woven textiles tend not to stretch out of shape. Woven textiles also tend to be thinner. In addition, woven textiles are lighter because less yarn is required to cover the same area. However, one disadvantage of woven textiles versus knitted textiles is that creating a three-dimensional final woven product generally requires stitching together several distinct woven textile pieces. For many years, manufacturers relied on producing clothing by "cut and sew" techniques. Production of woven garments involved the multi-step process of weaving raw fabric sheets, cutting the fabric sheets into panels, and sewing the panels into three-dimensional garments. Stitching two distinct woven textiles together forms a seam. Different distinct woven textiles, and thus seams, are typically needed where the product changes dimension or adds a new part.

When different pieces of fabric are cut and sewn together, a certain amount of fabric will be wasted. Often at least 15% of flat woven fabric is discarded during the cutting operation. Additionally, cutting and sewing fabrics is typically an expensive manual process. With this in mind, there is an advantage in making seamless garments in the garment manufacturing industry in order to reduce both material and labor costs, and to leverage economies of scale.

To address some of these issues, circular looms have been developed that can quickly produce clothing. For example, U.S. Patent Application Publication No. US2016/0281277, incorporated herein by reference, describes techniques for creating a three-dimensional woven textile product. The disclosed three-dimensional weaving technology can be used to create various textile products. However, current circular looms are designed to weave at a fixed output size, i.e., the looms produce woven tubes at a constant diameter. The circular looms can be re-configured to weave at different diameters, but this involves re-threading the machine and physically replacing several components. Due to this constraint, current circular looms cannot continuously weave fabric with varying diameter and circular weaving is commercially limited to constant diameter woven outputs.

U.S. Patent Application Publication No. US2020/0048799, which is also incorporated herein by reference, discloses a system and method for producing seamless woven materials that are variable in each of three dimensions. The system and method generally operate by altering heddle positions to impart three-dimensional structure to a woven fabric. Weft yarn is woven into a set of warp yarns that have been individually raised or lowered along a particular cross-section, essentially locking the weave into an intended 3-dimensional form. However, such an arrangement cannot be easily altered during manufacture. Also, such an arrangement is complex and expensive as the arrangement requires each individual heddle to have a motor and/or actuator.

Thus, there is a need for a system and method that can efficiently manufacture irregularly shaped woven fabrics with a three-dimensional structure having improved structural performance, and with reduced material. More specifically there is a need to form parts of garments that have varying diameters along their length, allowing production of various sizes on the same machine or to even fit an individual's unique body geometry. With the above in mind, in one aspect, there still exists a need in the art for a way to produce garments on-demand to eliminate waste. Direct three-dimensional weaving of complete garments or even parts of garments having a continuously varying diameter would reduce cut waste from the cutting process. Direct three-dimensional weaving of garments would also reduce waste from excess inventory. There also exists a need to eliminate waste from cutting patterns and reduce production time and other costs associated with cut and sew production.

SUMMARY OF THE INVENTION

The present invention is directed to a system and method for continuously weaving fabric products such as clothing, textiles, or even diverse items such as composite structures, inflatable structures, medical devices, fire hoses or bags, having a varying diameter. The weaving is conducted with a loom comprising a variable diameter weaving ring having a diameter that is altered during production of the clothing. Individual heddles are assembled in groups to form heddle units. Independently actuated heddle units are employed to further control the weaving process. Each of the heddle units includes an actuator for moving the heddle units. Alternatively, the heddle units are driven with a mechanical cam or linkage system. The heddle units are modular, and each heddle unit can be replaced as needed for repair or other reasons. Shuttles are provided with a bobbin to support a weft yarn and a weft insertion arm attached to each shuttle.

In order to compensate for the varying size of the weaving ring, the weft insertion arm is configured to move radially inward and outward in response to the changing diameter of the weaving ring. An adjusting unit or system is configured to adjust the position of the weft insertion arm. The system includes a linear rail for supporting the insertion arm and an actuator to move the weft insertion arm along the rail. One end of the arm is supported on the shuttle and the other end of the arm supports an eyelet. The weft extends from the bobbin to a sensor that detects weft breakage. The weft yarn extends through the sensor to the eyelet in the insertion arm. This arrangement allows for the weft to be inserted where the warp yarns meet the weaving ring and provides for improved continuously variable weaving. Preferably the sensor is a spring biased mechanism that supports the weft yarn. The weft applies pressure against the spring biased mechanism in the sensor. If the weft yarn breaks, the spring biased mechanism rotates and activates the sensor.

In alternate embodiments, the weft insertion arm preferably moves in non-radial and/or at least non-linear trajectories. For example, combinations of revolute joints can be used to accomplish similar desired motion profiles. There are various straight-line mechanisms which may be employed to accomplish these goals. In these alternate embodiments, the weft insertion point, i.e., the tip of the insertion arm, still moves in an effectively radial manner, but the arm itself may take another trajectory.

In combination with the adjustment of the weaving ring, the heddle units must dynamically change weave patterns to accommodate varying weave diameters. Each time a weft line crosses a warp line, an incremental amount of fabric length is added to the total circumference of the woven output. By alternating the weave pattern of the heddle units, the number of weft crossings can be altered in a manner that reduces the total circumference of the woven output in coordination with the adjustment of the weaving ring. Common weave patterns include 2×1 twill, 3×1 twill, and 4×2 twill, although any arbitrary arrangement of warp lines is possible. Specifically, 2×1 twill weaves, which have more weft crossings, are appropriate for larger diameter outputs, 3×1 twill weaves, with fewer weft crossings, are appropriate for medium diameter outputs, and 4×2 twill weaves, with even fewer weft crossings, are appropriate for small diameter outputs.

The variable diameter weaving ring is preferably made of a flexible nylon band. A portion of the flexible band is placed in a circle to form the variable diameter weaving ring, while another portion of the flexible band extends beyond the ring and is stored on a take-up mechanism. Preferably, the loom has a plurality of support arms for supporting the variable diameter weaving ring. Each arm includes a pivotably mounted guide configured to slidably support the variable diameter weaving ring. More specifically, each guide preferably includes two fingers configured to support the variable diameter weaving ring slidably therebetween. Other support configurations are also preferred, including rollers, hybrid roller-finger tongs, and single finger tongs. The diameter of the weaving ring is increased by moving the support arms radially outward and moving some of the flexible band from the take-up mechanism. The arms are mounted for synchronous motion so as to allow the arms to move radially outward at the same time and to ensure the weaving ring maintains a circular shape as the ring expands its diameter.

In operation, warp yarns are pulled off storage bobbins and brought to the heddles. The heddles are individually actuated to control the warp yarns as the warp yarns are weaved with the weft yarns. The warp yarns are switched by the heddles from an upper position to a lower position. The line the warp yarns follow, from the heddles in the upper position to the weaving ring and the line the warp yarns follow from the heddles in the lower position to the weaving ring, define a warp shed. During weaving the shuttles bring the weft yarn through the warp shed and the heddles switch between upper and lower positions, thus causing the weft yarn to be woven into the warp yarns. Continuously weaving fabric with the circular loom includes varying the diameter of the weaving ring, while moving the support arms and changing the heddle weave pattern in a synchronous manner, and moving part of the flexible material that forms the ring to or from the take-up mechanism. As indicated above, to compensate for the changing diameter for the weaving ring, weaving also includes adjusting the position of the weft insertion arm along the linear rail system on each shuttle.

This overall approach allows for the continuous weaving of fabric whose diameter varies along the length of the output, thereby enabling the direct weaving of garment components (i.e., single pant legs, shirt sleeves, dresses, etc.). The system can also be used to produce bifurcated outputs which would allow for the direct weaving of complete garments. This approach to textile manufacturing is analogous to 3D printing.

Additional objects, features and advantages of the present invention will become more readily apparent from the following detailed description of preferred embodiments when taken in conjunction with the drawings wherein like reference numerals refer to corresponding parts in the several views.

BRIEF DESCRIPTION OF THE DRAWINGS

The disclosure may be more completely understood in consideration of the following description of various illustrative embodiments in connection with the accompanying drawings.

FIG. **1** is a perspective view of a loom in accordance with a preferred embodiment of the invention.

FIG. **2** is a top view of the loom shown in FIG. **1**.

FIG. **3** shows a close-up view of an adjustable weaving ring from the loom of FIG. **1**.

FIG. **4** is an upper perspective view of support arms holding the weaving ring of FIG. **3**.

FIG. **5** is a lower perspective view of the support arms holding the weaving ring of FIG. **3**.

FIG. **6** shows the support arms of FIGS. **4** and **5** being connected to a synchronizing mechanism.

FIG. **7** shows a take-up mechanism for storing excess portions of a flexible band forming the weaving ring.

FIGS. **8-10** show the support arms progressively retracting to accommodate an expanding weaving ring.

FIG. **11** shows two shuttles passing through the warp shed and the arms for supporting the weaving ring.

FIG. **12** is a close-up view of a shuttle from the loom of FIG. **1** and shows details of an insertion arm.

FIG. **13** is a top view of synchronization sensors for controlling the heddles of the loom in FIG. **1**.

FIG. **14** is a perspective view of the sensors of FIG. **13**.

FIGS. **15** and **16** show a detailed view of a heddle unit of the loom shown in FIG. **1**.

FIG. **17** shows a pair of pants made by the loom of FIG. **1**.

FIG. **18** shows an arrangement of magnetic sensors used for synchronizing the weaving ring, heddles, and shuttle.

FIG. **19** is a side view an alternative arrangement of the heddle units.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The following detailed description should be read with reference to the drawings in which similar elements in different drawings are numbered the same. The detailed description and the drawings, which are not necessarily to scale, depict illustrative embodiments and are not intended to limit the scope of the disclosure. Instead, the illustrative embodiments depicted are intended only as exemplary. Selected features of any illustrative embodiment may be incorporated into another embodiment unless clearly stated to the contrary. While the disclosure is amenable to various modifications and alternative forms, specifics thereof have been shown by way of example in the drawings and will be described in detail. It should be understood, however, that the intention is not to limit aspects of the disclosure to the particular illustrative embodiments described. On the contrary, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the disclosure.

Definitions

As used throughout this application, the singular forms “a”, “an” and “the” include plural forms unless the content clearly dictates otherwise. In addition, the term “or” is generally employed in its sense including “and/or” unless the content clearly dictates otherwise.

“Yarn” refers to any string-like input to the weaving process. Yarn is a generic term for a continuous strand of textile fibers, filaments, or material in a form suitable for knitting, weaving, braiding, or otherwise intertwining to form a textile fabric and is often used interchangeably with “threads” and “lines.”

“Weave” refers to a system, or pattern of intersecting warp and filling yarns. The term, “Weave”, is used to describe a large area of textiles that are not knitted or are non-woven fabrics. Plain, twill, and satin are all types of weaves.

“Weft and warp” are terms that refer to the constituent yarns within a weave. The warp yarns run longitudinally to the direction of production while the weft yards run latitudinally to the direction of production and are sometimes called “filling yarns”.

“Threads per inch” is a measure of density of a fabric.

“Ends per inch” (EPI) is a similar measurement used when looking at the warp yarns while “picks per inch” (PPI) is used when looking at the weft yarn.

“Heddles” refers to structures usually shaped as a loop or eyelet that is able to control the movement (shedding) of the warp yarns. The specific construction of a heddle can vary within different machines.

“Shed” refers to a temporary separation between upper and lower warp yarns and is often used interchangeably with “warp shed.” A warp shed is also a triangularly shaped opening formed in the warp lines as the heddles move. The term also is often used as a verb to describe the action of the upper and lower warp yarns switching positions.

A “shuttle” is a movable loom component that acts as a carriage for the weft line and travels through the warp shed to deposit the weft line.

“Weft insertion” refers to the act of inserting weft into a weave usually via a shuttle with a weft bobbin.

“Weft insertion point” refers to a point set radial distance away from the weaving ring, where the weft is deposited.

“Crimp” refers to the waviness of a fiber. More specifically, crimp is the measure of the degree of waviness present in the yarns inside a woven fabric due to interlacement.

“Cover factor” refers to the ratio of area covered by the yarns to the total area of the fabric.

Overview

FIG. **1** shows a perspective view of a loom **10** in accordance with a first preferred embodiment of the invention. Loom **10** is a circular loom which can be thought of as a series of flat looms arranged in a circle. The operating principles are generally the same as a flat loom, with the major difference lying in the continuous travel of one or more shuttles **15**, one of which is labelled in FIG. **2**, which depicts a top view of loom **10**. Loom **10** has six shuttles, of which four are shown. Loom **10** may have as few as one shuttle and may have as many as can physically fit within the diameter of loom **10**, however, six is preferable. Due to the circular shape of loom **10**, during operation, shuttles **15** will pass by heddle units **20**. As one of shuttles **15** exits a warp shed of one of heddle units **20**, the shuttle will enter the warp shed of an adjacent heddle unit. Some of heddle units **20** are upright (such as at **25**) while some are positioned upside down (such as at **30**). Upside down heddle units **30** provide a space **35** for an operator to access an inner portion of loom **10**. While not shown in FIG. **1**, all heddle units **20** could be mounted upside down and such an arrangement is considered preferable. Heddle units **20** are adjustable. Although not shown in FIG. **1**, a supply of yarn is provided to heddle units **20** during operation of loom **10**.

With reference to FIGS. **1** and **2**, loom **10** includes a variable diameter weaving ring **45** (FIG. **2**) and a plurality of variable position weft insertion arms **50** with one arm being positioned on each shuttle **15**. Loom **10** includes a system of individually actuated heddle units **20** all controlled by a heddle control board **522** (FIG. **1**). Preferably loom **10** has **36** individually actuated heddle units **20** and each heddle unit has twenty individual heddles of which only eighteen are used during weaving. However, if loom **10** is made larger many more heddle units would preferably be provided and there also may be more heddles per unit. Preferably, loom **10** has six weft insertion shuttles **15**, four of which are shown in FIG. **2**, and one variable diameter weaving ring **45**.

Variable Diameter Weaving Ring

Turning now to FIG. **3**, variable diameter weaving ring **45** is located where warp lines **80** meet weft lines **85** to form a weft insertion point **90** to create a fabric product **100**. A fell line **105**, which is the edge of the weaving where the last weft line **85** was placed, is an interface where unwoven warp lines **80** become woven fabric product **100** when interlaced with weft line **85**. Preferably, the bottom of the weaving surface of weaving ring **45** is continuous and smooth so as to avoid tangled or breakage of warp lines **80** during weaving. A set of support guides **115** supports weaving ring **45**.

As best seen in FIGS. **4** and **5**, variable diameter weaving ring **45** is formed as part of a flexible band **125** supported by five guides **115**. A plurality of support arms **130** support guides **115**. Flexible band **125**, which could also be described as semirigid, creates a continuous weaving surface. Flexible band **125** overlaps itself at one overlap point or location **155** and the overlap of excess band material **190** becomes more or less as the circle formed by flexible band **125** grows larger or smaller.

Support arms **130** move in synchronism to achieve a proper weaving action. A chain drive **195** (see FIGS. **6** and **7**) guarantees synchronous motion between all of support arms **130** and helps maintain a circular output that is always centered around an output axis **196** in the Z direction of loom **10**. While chain drive transmission **195** is a preferred synchronizing mechanism, other options are possible. For example, timing belts, ring gears, cam mechanisms and other linkages could also be employed. If a non-circular output for fabric product **100** is desired, for example, an oblong or elliptical output, or an output that is not centered around output axis **196**, support arms **130** can be individually actuated. However, loom **10**, as shown, is set up to produce a circular fabric product **100**. Therefore, support arms **130** are shown coupled together using a chain **200** which engages with sprockets **210** of chain drive transmission **195**, as seen in FIGS. **5**, **6** and **7**.

Support arms **130** passively follow the shape of flexible band **125**. Support arms **130** function to provide support along output axis **196** of loom **10**. Alternatively, support arms **130** may be moved with either a single actuator moving all of support arms **130** or each arm could be fitted with an individual actuator. Each arm of support arms **130** is preferably provided with a joint encoder **230** (FIG. **6**) for indicating the angular position of a respective arm. However, loom **10** can be made to function with only one joint encoder on a single support arm. Support arms **130** continuously provide support for flexible band **125** along output axis **196** as flexible band **125** forms weaving ring **45** that changes diameter. The number of support arms **130** required is dependent on the maximum unsupported band length **235** (FIG. **4**) that a given band material can support before buckling. If there are just a few support arms **130** unsupported band length **235** increases. Unsupported band length **235** also increases when the diameter of weaving ring **45** increases. Preferably, there are five support arms **130**, but fewer can be used. The use of fewer supports limits the maximum weaving ring diameter before increasing unsupported length **235** (FIG. **4**) leads to failure. More support arms **130** could be used, but that would limit the smallest weaving ring diameter before support arms **130** interfere with one another. However, for large weaving ring diameters more than five support arms are preferable and if material with greater flexibility is employed for the flexible band, more support arms would be needed to reduce the unsupported band length. Support arms **130** are preferably arranged normal to weaving ring **45**. One of support arms **130** holds a joiner guide **240** (FIG. **5**) where excess band material **190** leaves weaving ring **45**. Alternatively, support arms **130** could be tangent to weaving ring **45**, specifically when weaving ring **45** is at its smallest diameter. The advantage is that band **125** converges at a central location that can be the position for a winder mechanism, described below.

As best shown in FIGS. **4** and **5**, guides **115** holding flexible band **125** in a circular configuration help form weaving ring **45**. Preferably, guides **115** have inner fingers **250** and outer fingers **251** that hold weaving ring **45** therebetween. Guides **115** are pivotally mounted on support arms **130**. Flexible band **125** slides through guide guides **115** as support arms **130** change position when more or less of flexible band **125** is fed into weaving ring **45**. Guides **115** are preferably made of aluminum and a low friction surface contact between the aluminum guides **115** and variable diameter weaving ring **45** allows for relative motion between guides **115** and flexible band **125**. Alternatively, a rolling connection, not shown, could be used between guides **115** and flexible band **125**.

As shown in FIGS. **4-7**, to adjust the diameter of the variable diameter weaving ring **45**, a desired command is sent by the control system **70** to weaving ring control board **253**. The desired command could be in the form of a single command, or a sequence of commands representing an entire weave. The weaving ring control board **253** then sends commands to a motorized winder **252**, which is provided to take in or let out calculated quantities of excess band material **190** (FIG. **5**) as needed. A motor **255** powers take-up winder **252** (FIG. **7**). Motor **255** rotates a gear reduction unit **260** which is connected to a pulley **265** by a coupling **270**. Pulley **265** is provided with a wheel **271** that stores excess flexible band material **190** (not shown in FIG. **7**) and pays out excess band material **190** as needed. A pulley encoder **275** senses the position of pulley wheel **271** and provides a signal which is used to determine how much of flexible band **190** has been dispensed. The size of the circle formed by flexible band **190**, i.e., the size of variable diameter weaving ring **45** can be measured directly or the diameter can be calculated by measuring the angular measurement of support arms **130** with arm encoders **230** (FIG. **6**). Support arms **130** are shown at a fully extended position in FIG. **8**, corresponding to the smallest diameter for weaving ring **45**; a middle position in FIG. **9**, corresponding to an intermediate diameter for weaving ring **45** and a retracted position in FIG. **10**, corresponding to a largest diameter for ring **45**. Variable diameter weaving ring **45** is designed so as not to interfere with warp shed **231**, shown in FIG. **11**, while still allowing operator access to the warp yarn lines **80** and weaving weft yarn lines **85**.

The flexible band forming weaving ring **45** must be stiff enough to withstand lateral torsional buckling, but flexible enough in the length axis to allow for bending. More specifically, variable diameter weaving ring **45** is stiff enough to avoid lateral torsional buckling under loading of warp lines **80** yet is flexible enough to curl into small diameters around output axis **196** (FIG. **4**) to create small diameter fabric product **100** as shown in FIG. **3**. Preferably the band is made of a polymer and, more preferably, Nylon 6/6 or another polymer, metal or composite material with a similar desirable combination of stiffness, strength, and frictional properties.

To synchronize the motion of the weaving ring **45** and the weft shuttle, loom **10** is equipped with one or more sensors configured to directly detect the presence of one or more shuttles at a known angular position within loom **10**. In one embodiment, the shuttles may be equipped with a magnet, which is detected by a stationary magnetic sensor placed on the periphery of loom **10**. The detection of a shuttle by the magnetic sensor is communicated to weaving ring control board **253** via synchronization control signal **72**, which upon receiving communication, may choose to perform a desired command.

Weft Insertion Arm

FIG. **12** shows a close-up view of one of weft shuttles **15** from FIG. **2**. In a most preferred configuration, loom **10** varies the radial location of weft insertion arm **50**, which passes through a linear guide or rail system **289** placed at the end of linear actuator **285** to support insertion arm **50** from side loading and to protect linear actuator **285** from binding. Weft insertion arm **50** receives weft yarn **85** (FIG. **3**). The location is moved by the linear actuator **285** that responds to a position sensor **290**, which is preferably a flexible potentiometer. Weft insertion arm **50** is preferably mounted on a shuttle **15**. Weft bobbin **291**, supporting weft yarn not shown, rotates about an axis defined on shuttle **15**. The weft yarn travels through an electromechanical weft break sensor **350** to an insertion finger **300** connected to the linear actuator **285**, where the weft is placed/inserted near variable weaving ring **45** and incorporated into the weave forming fabric product **100** as best seen in FIG. **3**. An onboard battery **320** powers the onboard shuttle control board or controller **325**, which controls linear actuator **285** and receives feedback from both linear position sensor **290** and weft break sensor **350**. Onboard shuttle control board **325** also communicates with loom control system **70** (FIG. **1**) via a wireless signal. A stepper motor **360** with an integrated encoder **370** transmits radial motion through a 1 to 1 belt drive system **380** to a lead screw drive assembly **390**, which translates the radial motion of belt drive system **380** to linear motion via a carriage **395** on a leadscrew **400**. Loom **10** also actively monitors for weft breaks via weft break sensor **350**.

Referring back to FIGS. **2** and **3**, as variable diameter weaving ring **45** changes diameter, insertion point **90** located near the end of arm **50**, is varied to ensure the correct length of weft yarn **85** is deposited and the correct tension is applied. Positional feedback from linear position sensor **290**, shown in FIG. **12**, to shuttle control board **325** and is used to actively check the position of insertion arm **50** as it travels the entire distance of linear actuator **285**.

As best seen in FIG. **18**, to synchronize the motion of weft insertion arm **50** and weaving ring **45**, shuttle **15** is equipped with one or more sensors configured to directly detect the presence of one or more landmarks at a known angular position within loom **10**. In one embodiment, shuttles **15** may be equipped with a magnetic sensor **410**, which detects a stationary magnet **412** placed on the periphery of loom **10**. The detection of magnet **412** by magnetic sensor **410** is communicated to shuttle control board **325** via synchronization control signal **71**, which upon receiving communication, may choose to perform a desired command. In a similar manner, sensor **510** provides synchronization control signals **72**, **73** to control boards **253** and **522**, respectively.

Weft Break Sensor

Referring back to FIG. **12**, weft break sensor **350** includes a magnetic hall sensor **460** and series of ceramic components. Weft yarn, not shown, will be routed through three contact points. The first contact point is a fixed ceramic element **475** over which the weft is routed. The second contact point is a spring loaded, ceramic eyelet **480** biased with a spring **481**, which has one degree of rotational freedom. The weft yarn is routed through eyelet **480**. The third contact point is the ceramic insertion finger **300**. When the weft breaks, the spring loaded, ceramic eyelet **480** rotates to reveal a magnet above a magnetic hall sensor **460**. Sensor **460** sends a digital signal to shuttle control board **325**.

Electronic Control

As seen in FIG. **12**, shuttle control board **325** is powered by battery **320**. For example, a commercially available 6s LiPo battery could be used. Shuttle control board **325** is a specialized control board. A wireless communication board **326** is a separate wireless connectivity module that receives signals from main control system **70** of loom **10** (FIG. **1**). The wireless communication board **326** can operate using different technologies, including but not limited to WiFi, Bluetooth, Zigbee, or radio. Wireless communication board **326** is connected to shuttle control board **325** via wired connection and relays commands from main control system **70** to shuttle control board **325**. Shuttle control board **325** can check for commands and report errors. Shuttle control board **325** preferably uses Modbus, which is a communication protocol that allows for communication between programmable logic controllers. However, other communication protocols could also be employed. The communication protocol is preferably used to allow shuttle control board **325** to communicate with linear actuator **285** as well as the wireless modem. Shuttle control board **325** receives digital signals from weft break sensor **350** and analog signals from linear position sensor **290**. The battery charge is monitored by shuttle control board **325**.

The Heddles

On a standard circular loom, heddle units are mechanically coupled to the motion of a main core rotor and the shuttles via a cam track and lever arms. Individual heddle control is known in a linear loom, see US Patent Application Publication No 2020/0048799, incorporated herein by reference. In circular loom **10**, heddle units **20** (FIG. **1**) are not mechanically connected to the main core. Rotation of the main core of loom **10** triggers heddle transitions but not with a cam system. Instead, as best seen in FIGS. **14** and **15**, an array of hall effect sensors **510** are electronically connected to heddle units **20**. FIG. **13** shows a perspective view of loom **10** under shuttles **15**, while FIG. **14** is a perspective view of hall array sensors **510**. As seen in FIGS. **15** and **16**, showing a close-up view of heddle unit **20**, each heddle **500** has two operational states: high or low. Hall effect sensor **510**, acts as a synchronization sensor and triggers a heddle transition from high to low as shuttle **15** passes by sensor **510**. As shuttle **15** passes sensor **510**, it automatically triggers the pusher block **520** which travels between the high and low positions. A shuttle pusher arm **511** has a magnet **512** mounted thereon such that sensor **510** senses the passing of magnet **512**. Heddle transitions from low to high of the respective heddle **500** are also controlled by heddle control board **522** which may be a separate controller or be part of controller **70**.

As best seen in FIGS. **1**, **15** and **16**, each heddle unit has a belt driven pusher block **520** that travels between high and low positions. The block **520** moves groups of individual Jacquard hooks/fingers **521** between high and low positions. When moving in the upward direction, the Jacquard hooks/fingers **521** are pushed by pusher block **520**. When moving in the downward direction, the Jacquard hooks/fingers **521** are pulled down by individual springs attached to heddle eyelets. At the top of the travel, the Jacquard hooks/fingers **521** are selectively locked/released by an electromagnetic latching mechanism. Heddle control board **522** determines which Jacquard hooks **521** are selectively locked or released, with the selection corresponding to any arbitrary weave pattern. The details of the latching mechanism are described in more detail in U.S. Pat. No. 5,839,481, incorporated herein by reference. Each of the Jacquard hooks **521** is correspondingly connected to a heddle eyelet which controls the position of the warp lines. Referring to FIG. **1**, the pusher block motion is driven by a brushless DC motor **550** attached to a timing belt loop **560**. Alternatively, the belt may be replaced with a mechanical linkage such as a crank rocker, cam linkage, or the like. The position of the pusher block is controlled via a geared encoder **570** attached to the main drive shaft. Alternatively, the position of the pusher block may be sensed directly.

The Jacquard mechanisms are integrated into heddle units **20**. Each of heddle units **20** has an individual drive motor **550** and is therefore modular. Heddle units **20** may be placed in a variety of positions on the loom and replaced as needed. Preferably thirty-six individual units are mounted in loom **10**. Each heddle unit preferably has at least 18 functional heddles **500** and each warp line is routed through a single heddle eyelet, allowing heddle unit **20** to control opening and closing of warp shed **231** (FIG. **11**). While weaving, heddle units **20** open sequentially to open shed **231** as shuttles **15** pass through shed **231**. This arrangement provides control of over seven hundred twenty warp lines. Other arrangements allow for greater numbers of heddles **500**, either by increasing the number of heddle units **20**, or the number of heddles per heddle unit. In certain weaves more than one warp line can be routed through a single heddle eyelet.

This arrangement allows for the opening and closing of shed profile **231** separately from the motion of shuttles **15**. As such the weave pattern in fabric product **100** can be varied. Loom **10** can weave patterns where multiple weft passes are made during a single warp shed opening, such as a basket weave. Common twill weaves can also be accomplished, including 2×1, 3×1, and 4×2 weaves. Certain twill weaves have reduced weft crossings and changing between these twill patterns allows for controlling the effective circumference of the fabric.

In an alternative embodiment shown in FIG. **19**, heddle units **20** are not physically co-located with the main core of circular loom **10** and are instead arranged at some distance from the core. Heddle units **20** may be arranged in groups, such that mechanical couplings and transmission elements can be shared between the units. Groups of heddle units **20** are known as a heddle bank **610**. Each heddle unit **20** may still maintain a unique shed motion but is mechanically indexed relative to its neighboring heddle unit within the heddle bank **610**. While weaving, the mechanical indexing allows heddle units **20** to open sequentially, generating a sinusoidal shed pattern in the loom core. When viewed from the side, as in FIG. **19**, the resulting heddle eyelet positions will resemble a sine wave. The sine wave travels with the angular motion of each shuttle, wherein each shuttle is captured in an open shed.

In this embodiment, the heddle units **20** may be mechanically coupled to the motion of the main core with mechanical transmission **620**. The heddle units **20** may optionally be electronically coupled to the motion of the main core, using synchronization methods previously described, or using other means known in the art such as encoders. In either approach, the individually actuated heddles are still electronically synchronized with the motion of the main core, the weaving ring, and the shuttles, thus allowing varying weave patterns to be created.

As best seen in FIG. **19**, the heddle eyelets **630** and springs **640** are still co-located with the main core of circular loom **10**. The eyelets **630** are mechanically coupled to the Jacquard hooks **521** by means of Jacquard cord **650**. Jacquard cord **650** can be routed in a variety of arrangements, allowing for the large mechanical components of heddle units **20** to be mounted remotely from the main core of circular loom **10**, thus improving operator access to the weaving area of loom **10**. As such, additional heddles or heddle units **20** can easily be added.

During operation, with general reference to the figures described above, when fabric **100** is to be woven, master controller **70** determines an angular position for support arms **130** based on a desired diameter of variable diameter weaving ring **45**. If the diameter of weaving ring **45** is to be reduced, take up winder **252** will wind up excess band material **190** until a target position value is detected by the joint encoder **230** on support arms **130**. Conversely if the diameter of weaving ring **45** is increasing, take-up winder **252** will let out excess band material **190** while chain drive **195** moves support arms **130** to a desired position. Adjustments to the weaving ring diameter are made dynamically while weaving, based on a desired output set by control system **70**. Weft shuttles **15** are powered by a main motor (not separately shown) on loom **10** to move shuttles **15** along a guiding track (also not shown). Each weft shuttle **15** deposits weft yarn **85** near variable diameter weaving ring **45** from weft bobbin **280** on shuttle **15**. Heddle units **20** transition before and after weft shuttle **15** has passed. Weft shuttle **15** is encapsulated within warp shed **231** as best seen in FIG. **11**. The transitioning warp yarns **80** capture the deposited weft yarns **85** to create the structure of the weave, namely fabric product **100** as shown in FIG. **3**.

In order to create woven fabric product **100**, the weave patterns of heddle units **20**, diameter of weaving ring **45**, and position of shuttle weft insertion arm **50**, must all vary in a synchronized fashion. To accomplish this, a counter-based approach may be employed. In this paradigm, heddle units **20**, weaving ring **45**, and weft shuttle **15** are all equipped with separate control boards, which taken together with loom controller **70**, comprise a distributed control system. Loom controller **70** sends separate weave instructions to heddle unit control board **522**, weaving ring control board **253**, and shuttle control board **325**, where the instructions are then performed locally in response to the synchronization control signal **71**. This allows each device to maintain a synchronized count reflecting the number of times synchronization control signal **71** has been received, thus ensuring that all devices are performing their desired actions in coordination. The weave instructions may be configured such that desired actions are only performed at specified count values. The weave instructions may be created in advance, in accordance with desired properties of woven fabric product **100** or set directly by an operator while weaving.

The product **100** may be attached to other sections of weave to form a garment **700** as best seen in FIG. **17**. Garment **700** may have first and second legs **710**, **720** stitched together at a seam **740** to form the overall garment **700**, such as a pair of trousers. Each leg **710**, **720** of garment **700** is preferably formed with no seams.

As noted above, the previously employed circular looms are designed to weave at a fixed output size which creates a fabric shape with a constant diameter. Such looms can be reconfigured to weave at different diameters, but several components of the loom would have to be replaced and the loom would have to be rethreaded to make such a change in diameter. Due to this constraint, such looms cannot continuously weave fabric with varying diameter. Based on the above it should be readily apparent that the subject loom, having a variable diameter weaving ring and independently actuated heddles, is able to continuously weave fabric whose diameter varies along the length of the fabric as it is produced.

Various other changes may be made in the final product. For example, the output fabric density also dictates both the final size and quality of woven fabric product and can be changed in the preferred embodiments described above. Fabric density is defined in the textile industry as Ends Per Inch ("EPI") and is a count of the number of warp lines per inch of fabric. To maintain fabric appearance and quality, EPI of the output fabric must be kept quasi-constant across all weaving diameters; this is accomplished via thread manipulation methods such as thread packing or thread dropping. Because the above-described methodologies involve individual control of warp lines, independently actuated heddles must be utilized such as those described above. In thread packing, multiple adjacent lines will move in tandem, effectively behaving as a single line while they are included into the weave. In thread dropping, lines are selectively left out of the weave and are later trimmed from the output fabric. Varying weave patterns between common twill configurations, such as 2×1, 3×1, and 4×2 can also be used to reduce the number of weft crossings for an intended weave diameter, thus reducing the effective woven circumference of the fabric.

With the construction and operation detailed above, the circular loom of the invention can directly weave components of garments such as single pant legs, shirt sleeves, dresses etc. Complete garments can be advantageously, directly woven on demand.

The invention claimed is:

1. A circular loom for continuously weaving fabric with varying diameter, the loom comprising;

a variable diameter weaving ring;

a set of independently actuated heddles each configured to control a shed of a warp line;

at least one shuttle including a weft insertion arm, wherein the weft insertion arm is configured to adjust with a changing diameter of the weaving ring; and

a control system for controlling actions of the weft insertion arm, the set of independently actuated heddles, the weaving ring, and the at least one shuttle in response to the changing diameter of the weaving ring, wherein the control system electronically synchronizes the actions of the heddles, the weaving ring, and the at least one shuttle.

2. The circular loom of claim **1**, further comprising a rail for supporting the weft insertion arm and an actuator to linearly adjust the weft insertion arm along the rail.

3. The circular loom of claim **1**, further comprising an array of magnetic sensors employed in synchronizing the actions the heddles, the weaving ring, and the at least one shuttle.

4. The circular loom of claim **1**, wherein the control system is configured to establish the actions of the heddles, weaving ring, and the at least one shuttle based on weave instructions created in accordance with desired properties of a woven fabric product.

5. The circular loom of claim **1**, wherein the control system includes at least two of a master loom control board, a heddle control board, a shuttle control board, and a weaving ring control board.

6. The circular loom of claim **1**, further comprising two support arms mounted for synchronous motion, wherein each support arm includes a pivotable mounted guide configured to slidably support the variable diameter weaving ring.

7. The circular loom of claim **6**, wherein each guide includes multiple fingers or rollers configured to support the variable diameter weaving ring.

8. The circular loom of claim **6**, wherein the variable diameter weaving ring is made of a flexible band.

9. The circular loom of claim **8**, further comprising a take-up mechanism and wherein a portion of the flexible band is placed in a circle to form the variable diameter weaving ring and a portion of the flexible band is stored on the take up mechanism, whereby the diameter of the weaving ring is increased by moving the support arms and some of the flexible band from the take up mechanism.

10. The circular loom of claim **1**, wherein the at least one shuttle includes a sensor for detecting weft breakage.

11. The circular loom of claim **1**, wherein the control system is configured to dynamically adjust the diameter of the variable diameter weaving ring based on a desired output.

12. The circular loom of claim **11**, wherein the control system is configured to communicate with at least one shuttle to control a weft insertion point based on the diameter of the weaving ring.

13. The circular loom of claim **12**, wherein the control system is configured to communicate with the set of independently actuated heddles to control shedding of the warp lines to achieve a desired weave pattern.

14. A method for continuously weaving fabric with varying diameter with a circular loom including a weaving ring, a set of heddles and at least one shuttle said method comprising:

varying a diameter of the weaving ring;

independently actuating the set of heddles to control a shed of a warp line;

adjusting a position of a weft insertion arm for the at least one shuttle with a changing diameter of the weaving ring;

controlling actions of the weft insertion arm, the set of heddles, the weaving ring, and the at least one shuttle in response to the changing diameter of the weaving ring; and

electronically synchronizing the actions of the heddles, the weaving ring and the at least one shuttle.

15. The method according to claim **14**, wherein the circular loom includes a rail for supporting the weft insertion arm, said method further comprising controlling an actuator to adjust the weft insertion arm along the rail.

16. The method according to claim **15**, further comprising adjusting a position of the weft insertion arm with an actuator to linearly move the weft insertion arm along the rail.

17. The method according to claim **14**, further comprising electronically synchronizing the actions of the heddles, the weaving ring, and the at least one shuttle based on instructions created in accordance with desired properties of a woven fabric product.

18. The method according to claim **14**, wherein the loom includes two support arms, wherein varying the diameter of the weaving ring includes moving the support arms in a synchronous manner.

19. The method according to claim **18**, wherein loom includes a take-up mechanism, the weaving ring is made of a flexible band and a portion of the band is mounted on the take-up mechanism, and wherein varying the diameter of the weaving ring further comprises increasing the diameter of the weaving ring by moving the support arms away from a center of the weaving ring and moving a portion of the flexible band from the take-up mechanism.

20. The method according to claim **14**, further comprising actuating each said heddle with an individual actuator located on a respective said heddle.

21. The method according to claim **14**, wherein the at least one shuttle includes a sensor, and the method further comprises detecting weft breakage with the sensor.

22. The method according to claim **14**, further comprising dynamically adjusting the diameter of the weaving ring based on a desired output and controlling a weft insertion point based on the diameter of the weaving ring.

23. The method according to claim **22**, further comprising communicating with the set of independently actuated heddles to control shedding of the warp lines to achieve a desired weave pattern.

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