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Croche-Matic: a robot for crocheting 3D cylindrical geometry

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***Abstract*—Crochet is a textile craft that has resisted mechanization and industrialization except for a select number of one-off crochet machines. These machines are only capable of producing a limited subset of common crochet stitches. Crochet machines are not used in the textile industry, yet mass-produced crochet objects and clothes sold in stores like Target and Zara are almost certainly the products of crochet sweatshops. The popularity of crochet and the existence of crochet products in major chain stores shows that there is both a clear demand for this craft as well as a need for it to be produced in a more ethical way.**

In this paper, we present Croche-Matic, a radial crochet machine for generating three-dimensional cylindrical geometry. The Croche-Matic is designed based on Magic Ring technique, a method for hand crocheting 3D cylindrical objects. The machine consists of nine mechanical axes that work in sequence to complete different types of crochet stitches, and includes a sensor component for measuring and regulating yarn tension within the mechanical system. Croche-Matic can complete the four main stitches used in Magic Ring technique. It has a success rate of 50.7% with single crochet stitches, and has demonstrated an ability to create three-dimensional objects.

***Index Terms*—Mechanism Design, Product Design, Development and Prototyping, Domestic Robots.**

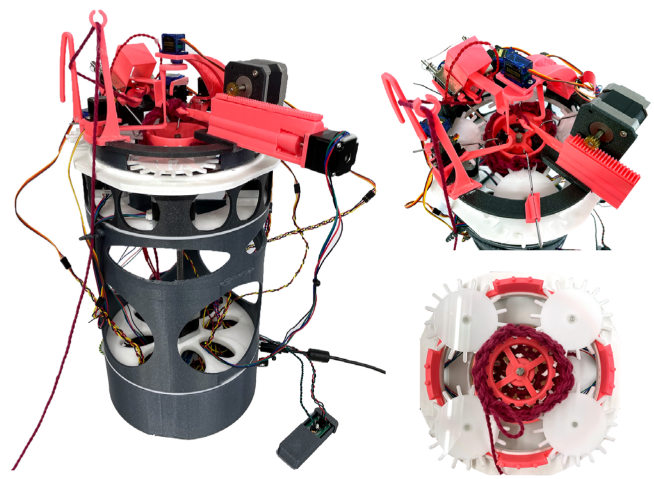

Fig. 1. The Croche-Matic robot prototype. The pink and grey components are 3D printed using PLA, and the white elements are laser-cut acrylic. The color pink denotes that the mechanical axis interacts with the crochet work object. The bottom right image shows the crochet work object rotation axes used to rotate the crochet object.

I. Introduction

Crochet and knitting are two distinct process that are often confused. A key difference between the two is that knitting uses two needles and crochet uses a single hook. Knitting has been commonly used in industrial textile production since its mechanization in 1589 by Rev. William Lee and the establishment of the UK's textile industry in 1750 [1]. Crochet has a wider variety of stitches and fabric textures than knitting, and has been used in mathematics for modeling hyperbolic geometry [2]. Crochet has been used to create artificial ligaments that mimic the force displacement of a human hand ligament [3]. Crochet research is less prevalent in literature because crochet has avoided mechanization except for a select number of one-off machines [4] [5]. There do exist a large number of "crochet-like" or warp knitting machines [6] [7] [8]. However, none of these existing machines are capable of generating 3D cylindrical geometry (see example in Fig. 2), and only one of these machines [4] is capable of creating single crochet stitches, one of the foundational stitch types.

The popularity of crochet clothes and objects is apparent in their inclusion in popular clothing brands and the presence of crochet objects and crochet patterns on online marketplaces such as Etsy. While there are no means of mechanized crochet, mass-produced crochet clothes are nevertheless sold at low costs in chain clothing stores like Target, Zara, and Forever21. These crochet clothes are likely the products of sweatshop-style production houses where workers earn low wages for tedious and exhausting work [9]. There is a clear demand for this popular textile to be produced in a more ethical way.

Croche-Matic is a machine that has the potential to create three-dimensional crochet garments, and has already successfully completed chain, single crochet, increase, and decrease stitches. This paper describes the machine design on the basis of Magic Ring technique, the mechanical axes that were needed for completing crochet stitches, and the testing and performance of the machine.

Fig. 2. A crochet object (left) and a knitted object (right) which carries the same properties as imitation-crochet warp knitting. Both objects use the same pattern, hook and needle size, and type of yarn. The crochet object holds its three-dimensional form better than the knitted object, which is more malleable.

II. Related Work

A. Existing Crochet Machines

There are two existing machines that can create crochet stitches [10]. The first, ”Luftmaschen Häkelmaschine” (Chain Stitch crochet machine) is a machine that creates chain stitches in series [5]. The second is able to crochet a small rectangular patch of fabric using chain stitches and single crochets [4].

B. Other Related Machines

Other machines exist that can generate ”crochet-like” stitches. The most common type of these machines are warp knitting machines [6] [7] [8]. Warp knitting machines use a hooked needle similar to a crochet hook and can create transverse chain stitches (diagonal or staggered stitches rather then vertical stitches found in standard knitting). These machines cannot replicate any crochet stitch beyond chain stitches, however, which limits their output to a small fraction of the design space. There are also machines like the Merrow crochet sewing machines [11], which create border stitches that imitate the aesthetic of a crochet border around a fabric. There is also research in developing crochet accessories that could support a fully mechanical crochet machine, such as a counting crochet hook that keeps track of stitches [12]. These machines can create imitation stitches but cannot reproduce crochet stitches as done by hand. The same diameter needle and hook, and type of yarn will yield a denser and tighter fabric with hand crochet than with knitting. This tightness is useful for creating objects that maintain their geometry (Fig. 2).

C. Crochet Simulation and Mathematical Modeling

There are many research projects that attempt to simulate crochet digitally to visualize the different stitches [13] and the geometric outcomes of crochet patterns [14] [15].

Crochet has been used to model complex geometries, and in particular was the original modeling medium for hyperbolic geometry [2] [16]. Crochet has also been used to physically model geometries like the Lorenz Manifold [17]. There is a plethora of research in modeling crochet and using crochet as a modeling method, but minimal research into developing a machine that can create crochet artifacts.

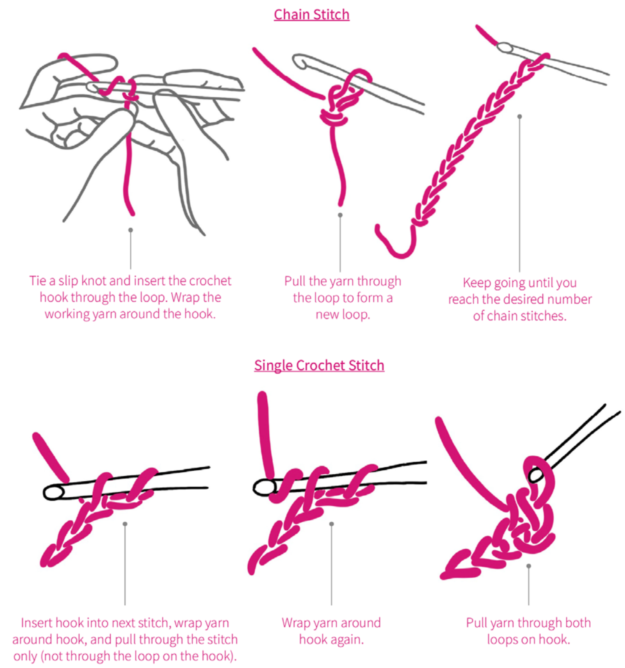

Fig. 3. Chain (top) and Single crochet (bottom) stitch diagrams.

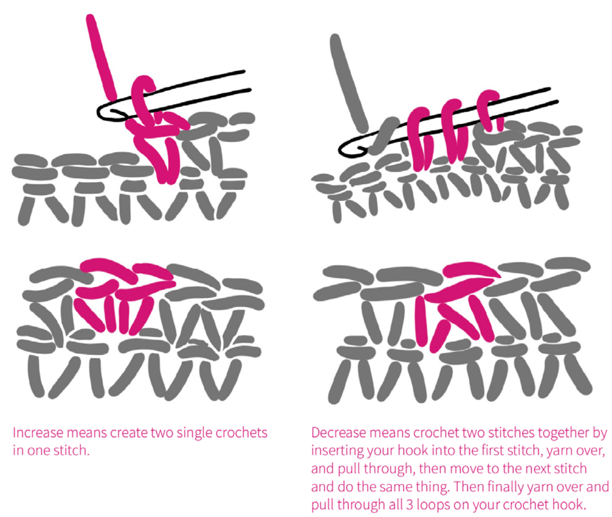

Fig. 4. Increase (left) crochet stitch and Decrease (right) crochet stitch diagrams.

Building a robot to crochet 3D cylindrical geometry would help to translate crochet simulation research into the physical world.

III. Machine Design and Development

The Croche-Matic (Fig. 1) is a robot capable of generating three-dimensional geometry. It has successfully demonstrated the four main crochet stitches used in Magic Ring technique. Two of these stitches, the increase and decrease stitch (Fig. 4), have never before (to the best of our knowledge) been successfully completed by a machine.

A. Magic Ring Crochet Analysis

Magic Ring Technique is a crochet method commonly used in the art of Amigurumi to create stylized three-dimensional enclosures. Magic Ring is initiated by wrapping yarn around the three middle fingers of the hand, crocheting a number of single crochets around the created ring, and continuing to crochet in a spiral. Increasing and decreasing the stitch count in a round creates larger or smaller circular rounds respectively. This differs from crocheting flat objects like scarfs or blankets, which are crocheted laterally back and forth. The spiral motion of stitching in Magic Ring allows for easier mechanization of crocheting 3D cylindrical geometry. Flat crochet pieces would likely require hand assembly to create 3D geometry.

The four common stitches used in Magic Ring crochet are chain, single crochet, increase, and decrease stitches (Fig. 4) (Fig. 3). Single crochets are the main stitch used in Magic Ring. Increase stitches are when two single crochets are created in the same base stitch, and decrease stitches are when two base stitches are crocheted together (Fig. 4).

Film and photography were used to analyze the hand motions of Magic Ring to determine the necessary mechanical motions for completing crochet stitches. There were six key motions found in these studies (Fig. 5). Three of the motions were hook motions and three were motions specific to the manipulation of the crochet work object or yarn. The six motions found in these studies (Fig. 5) provided the basis for the first six axes of the Croche-Matic.

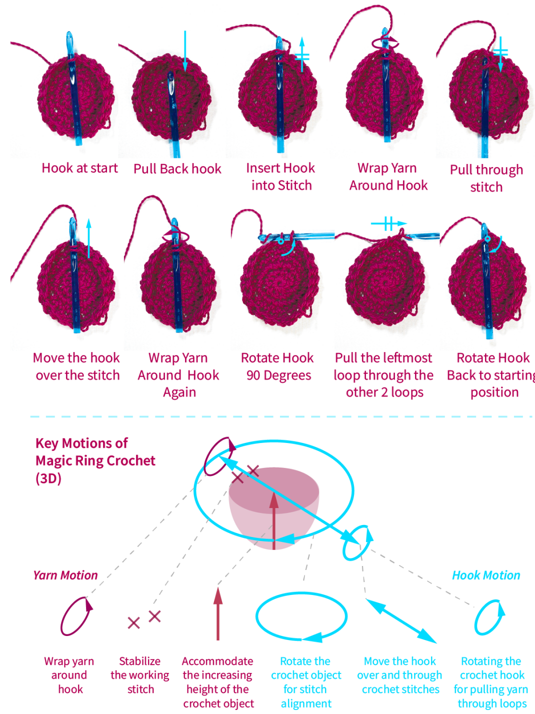

Fig. 5. Photographic analysis (top) of each position of the crochet object and hook after each hand motion step of Magic Ring, and a diagram (bottom) of the six observed motions of Magic Ring.

B. Machine Design Overview

The goal of Croche-Matic (Fig. 1) is to design and prototype a machine that can crochet three-dimensional objects and complete more stitch types then existing crochet machines. The machine is composed of three main sections (Fig. 6). These sections contain components made of 3D-printed PLA and laser cut acrylic. All parts were fabricated using a Prusa MK3 3D printer and a Thunder Nova CO2 laser cutter. The first section is the top-most ring of the machine. The top ring contains all of the axes necessary for completing crochet stitches, because in Magic Ring, the crocheter typically works into the top round of stitches. The pink 3D printed elements indicate that the attached axis touches the crochet object. These elements are aligned with the center of the crochet work object.

Below the top ring is the second section, containing the crochet work object and the work object rotation axis assembly (Fig. 1). The work object rotation axis assembly includes a central rod capped with a 3D-printed cylindrical element that is bordered by four laser-cut acrylic gears mounted to four NEMA 17 stepper motors. The crochet object is held in place between the rotating gears and the 3D-printed cylindrical element. When all four gears rotate simultaneously, they cause the crochet work object to rotate accordingly.

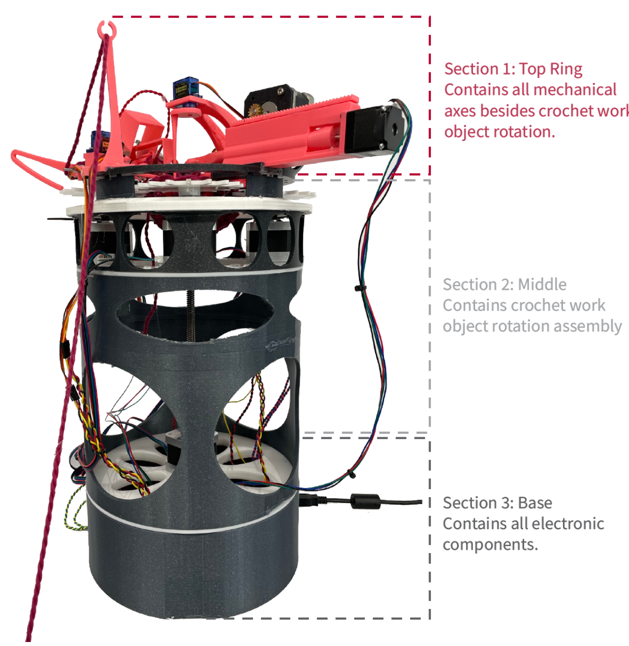

Fig. 6. The three sections of Croche-Matic. The first section is the top ring which contains all of the mechanical axes. The second section is the middle section below the top ring which contains the crochet work object rotation assembly. The third and final assembly is the base of the machine which houses all of the electronic components.

The third section of the machine is the base, which houses all of the electronics used to control the mechanical axes.

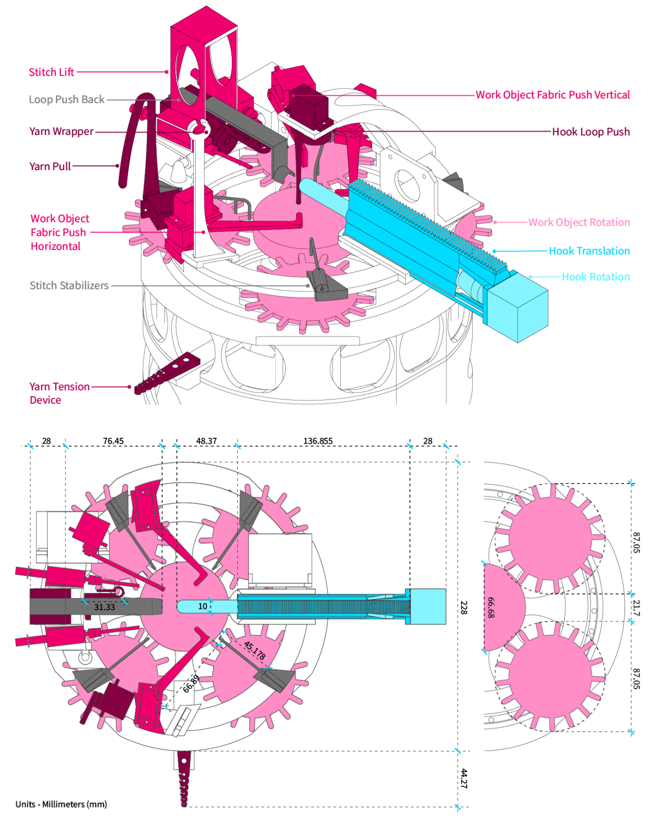

Fig. 7. Diagrams of the top assembly of the machine with call outs and dimensions for mechanical axes. The axes manipulating the crochet hook are noted in blue. The axes manipulating the crochet work object are noted in grey/white. The axes manipulating the working yarn or stitch are noted in pink.Dimension units are in millimeters.

The machine is controlled by an Arduino Mega and powered by a 5 V wall supply. All stepper motors are controlled by A4988 motor drivers and powered by a 16 V 2 A wall supply. Outside of the base is a controller with a start button that initiates the crochet stitch program, and a pause switch that was used for debugging without needing to restart the program.

C. Mechanical Axes for Crochet

Croche-Matic consists of nine axes or degrees of freedom (Fig. 7). Eight of these axes are mounted to the top ring of the machine. The ninth axis is the crochet work object rotation assembly. Five of these axes were designed based on the original six motions of Magic Ring technique (Fig. 5). These axes are noted below with an asterisk(*). The other four axes were added to more reliably manipulate the crochet work object and successfully complete crochet stitches.

Each axis performs a specific motion that was found to be necessary for successfully completing a crochet stitch. These axes are designed based on the Magic Ring analysis and extensive physical testing and prototyping. The nine axes are:

Hook Translation*: The hook translation axis (HTA) is responsible for moving the hook forward and backward through the crochet work object.

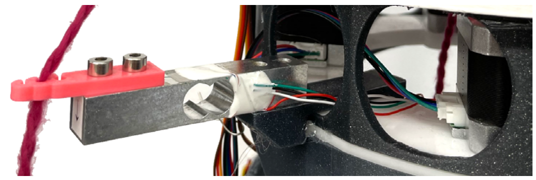

Fig. 8. Image of the Yarn Tension Sensor device. Yarn feeds through the 3D-printed component. Forces imparted by yarn tension are detected and recorded by the load cell mounted to the machine housing.

Hook Rotation*: The hook rotation axis (HRA) rotates the hook around its shortest dimension to orient the hook for catching and pulling the yarn through stitches.

Hook Loop Push: The hook loop push axis (HLPA) moves the loops currently on the hook out of the path of the hook translation axis (HTA).

Yarn Wrapper*: The yarn wrapper axis (YWA) wraps the yarn around the hook.

Yarn Pull: The yarn pull axis (YPA) releases tension built up from the yarn wrapper and hook translation axes.

Stitch Lift*: In crochet the hook needs to be inserted through the working stitch. The stitch lift axis (SLA) is the axis that grabs the working stitch and lifts it up to the level of the hook for insertion and lowers it afterward to not impede the next motion in the sequence.

Work Object Fabric Push Horizontal: The work object fabric push horizontal axis (WOFPHA) is designed to push the working side of the crochet fabric back towards the stitch lift axis. The crochet work object is pulled out of shape during the stitch motion sequence and must returned to its original position before rotating to the next stitch.

Work Object Fabric Push Vertical: The work object fabric push vertical axis (WOFPVA) is designed to push the working side of the crochet work object down so that the crochet hook does not get caught in the fabric when it moves over the stitch.

Work Object Rotation*: The work object rotation was previously described in Subsection III-B.

Other Important Non-DoF Elements: There are two additional elements in the Croche-Matic that are not DoFs. The first is the yarn tension device. The second is the four stitch stabilizing elements located around the top ring that prevent the crochet work object from moving too far above the level of the work object rotation.

Further description and visualization of each degree of freedom can be found in this paper's accompanying video.

D. Yarn Tension Device

The Croche-Matic includes a device to measure the amount of yarn tension in the mechanical system (Fig. 8). In domestic knitting machines, yarn tension devices are small components with holes of varying sizes, through which yarn is thread before entering the machine. Smaller holes introduce friction as the yarn moves through the device, increasing tension.

The Croche-Matic's tension device includes a 3D-printed component with six different sized holes (2.75, 2.5, 2.25, 2, 1.75, and 1.5 mm diameter). These sizes are based on the yarn used for testing, which was a cotton yarn approximately two millimeters thick. One end of the load cell is attached to the machine housing and the other end cantilevers out of the machine housing, holding the 3D-printed tension component. The yarn runs through the holes in the 3D-printed tension component. As the yarn passes through, the exerted force is measured by the load cell, and the data is streamed to a spreadsheet to keep track of tension during testing.

E. Stitch Programming

One of the main goals of Croche-Matic is to successfully complete the four common stitches found in Magic Ring technique. These four stitches are chain, single crochet, increase, and decrease (Fig. 3)(Fig. 4). To complete these stitches, four motion sequence programs were developed to be executed by a micro controller.

The chain stitch was the simplest program, as a chain stitch only requires three axes and five mechanical motions. The program for single crochet requires 30 distinct mechanical motions and utilizes all nine degrees of freedom. The working motion sequence for increases stitches requires 62 distinct mechanical motions. The working motion sequence for decrease stitches requires 42 distinct mechanical motions.

IV. Performance and Evaluation

A. Machine Set-Up

The crochet object used for testing was initiated by hand with 12 stitches in the round. The 12-stitch round has a diameter of 85 mm, and fits between the 75-mm diameter cylindrical cap and the 4 gears of the crochet work object assembly (Fig. 1). The crochet work object is mounted so that the work object rotation gear prongs insert into the row below the current round. The center of the working stitch must be aligned with hook translation axis.

The top ring of the machine is removed to mount the crochet object between the work object rotation gears and the central cylindrical cap. Then the top ring is placed back on the top of the machine and the hook rack assembly is inserted under the hook translation axis motor. The working loop of the crochet is looped around the crochet hook, and the working yarn is then threaded through the yarn wrapper, the yarn pull, and the yarn tension components (see accompanying video for machine set up reference).

B. Machine Prototyping and Testing

The single crochet motion sequence program was used for performance evaluation, as it is the most commonly used of the four main stitches in Magic Ring technique. The base of the crochet work object is started by hand. The yarn selected for testing is a medium cotton yarn because cotton yarns stretch less than acrylic yarns.

The testing sequence begins with aligning the center of the working stitch to the center of the crochet hook. After alignment, the machine is powered on, and the start button is pressed to initiate the stitch motion sequence. The machine is run continuously until a stitch failure was observed. If the machine completes the first stitch successfully, it moves onto the next stitch without interruption. If a failure occurs, the pause switch is flipped and the failure is fixed manually. If the failure could not be fixed during the pause, the machine is powered off, and all axes are manually reset to start the next stitch.

Tension testing was conducted after the single crochet testing sequence was developed, and the machine was able to successfully demonstrate multiple single crochet stitches in series. Twelve single crochet stitches were attempted for each of six different hole diameters (2.75, 2.5, 2.25, 2, 1.75, and 1.5 mm) in the tension device. The tension force during each test was recorded in a spreadsheet with notes describing any problems or reason for failure.

C. Results

The tension testing was conducted first to determine the correct amount of tension for subsequent single crochet testing. The two smallest diameter holes (1.5 mm and 1.75 mm) were too restrictive and caused the machine to stall before completing a stitch. For each of these holes, three failures occurred consecutively and testing was halted to prevent excessive tension from damaging the machine. The max tension forces recorded in these tests ranged from 14 to 28 grams (Fig. 10, blue tests in the graph).

The 2.0 mm hole had a 50% success rate for single crochet stitches. The failures that occurred on these tests happened later in the motion sequence than in the previous tests, and the max tension for failures was approximately 5 grams. The 2.25 mm and 2.5 mm holes had the highest success rates at 75%. All of the failures within these tests were the result of a malfunction of a mechanical DoF and were not related to tension. The largest diameter hole, 2.75 mm, also had a success rate of 75% but all of the failures from this test were the result of too little tension in the system. Because of the minimal tension, the crochet loops slipped off the hook, forming chain stitches instead of single crochet stitches. Of the two most successful tension hole sizes, the 2.25 millimeter hole was selected to be used for subsequent single crochet testing (Fig. 10, red colored tests in graph).

The results of the single crochet motion sequence are recorded in Fig. 9. Each test records if each axis was successful, and if the stitch was fully completed. If an axis fails and causes the stitch to be unsuccessful then the axis of failure is also noted in the table.

36 single crochet stitches were completed out of 71 attempts during testing, meaning the machine has a stitch completion success rate of 50.7%. A stitch was deemed completed if all of the mechanical motions were successful. However, the stitch was not always completed in the right location, as the crochet object has a number of holes in the crochet fabric that the hook could be inserted into instead of the proper next stitch. The longest number of consecutive

Axis Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Hook Translation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Hook Rotation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	S	S	S	Y	Y
Yarn Wrapper	Y	Y	Y	Y	Y	Y	-	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Stitch Lift Solenoid	Y	Y	N	N	Y	Y	-	Y	N	N	Y	N	Y	S	S	S	N	N
Stitch Lift Servo	Y	S	N	N	Y	Y	-	Y	N	N	Y	N	Y	S	S	S	N	N
Hook Loop Push Servo	S	N	-	-	S	Y	N	Y	Y	-	Y	-	Y	Y	Y	Y	-	-
Yarn Pull Servo	Y	Y	-	-	Y	Y	-	Y	-	-	Y	-	Y	Y	Y	Y	-	-
WOFPH - Right	N	Y	-	-	N	Y	N	Y	S	-	Y	-	Y	Y	S	S	-	-
WOFPH - Left	Y	Y	-	-	Y	N	-	S	S	-	Y	-	Y	S	S	S	-	-
WOFP- Vertical	Y	Y	-	-	Y	Y	-	Y	-	-	Y	-	Y	Y	Y	Y	-	-
Work Object Rotation	Y	Y	-	-	Y	Y	-	Y	S	-	Y	-	Y	Y	Y	Y	-	-
Stitch Completed?	Y	Y	N	N	Y	Y	N	Y	N	N	Y	N	Y	Y	Y	Y	N	N

Axis Name	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Hook Translation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y
Hook Rotation	Y	Y	Y	Y	Y	Y	Y	S	Y	S	Y	N	N	S	Y	Y	Y	Y
Yarn Wrapper	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y
Stitch Lift Solenoid	Y	N	N	Y	N	Y	S	Y	S	S	Y	Y	Y	Y	S	S	S	Y
Stitch Lift Servo	Y	N	N	Y	N	Y	S	Y	Y	S	Y	Y	Y	Y	S	S	S	Y
Hook Loop Push Servo	Y	-	-	Y	-	Y	-	Y	Y	Y	-	-	-	Y	Y	-	-	Y
Yarn Pull Servo	Y	-	-	Y	-	Y	-	Y	Y	Y	-	-	-	Y	Y	-	-	Y
WOFPH - Right	Y	-	-	Y	-	Y	-	Y	Y	Y	-	-	-	Y	Y	-	-	Y
WOFPH - Left	Y	-	-	Y	-	Y	-	Y	Y	Y	-	-	-	Y	Y	-	-	Y
WOFP- Vertical	Y	-	-	Y	-	Y	-	Y	Y	Y	-	-	-	S	S	-	-	Y
Work Object Rotation	Y	-	-	Y	-	Y	-	Y	Y	Y	-	-	-	Y	Y	N	-	Y
Stitch Completed?	Y	N	N	Y	N	Y	N	Y	Y	Y	N	N	N	Y	Y	N	N	Y

Axis Name	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Hook Translation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Hook Rotation	Y	S	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Yarn Wrapper	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
Stitch Lift Solenoid	N	Y	S	S	S	N	S	Y	Y	Y	S	S	S	S	Y	S	N	N
Stitch Lift Servo	N	Y	S	S	S	N	S	Y	Y	Y	S	S	S	S	Y	S	N	N
Hook Loop Push Servo	-	Y	Y	Y	-	-	-	Y	Y	Y	Y	Y	Y	-	Y	Y	-	-
Yarn Pull Servo	-	Y	Y	Y	-	-	-	Y	Y	Y	Y	Y	Y	-	Y	Y	-	-
WOFPH - Right	-	Y	Y	Y	-	-	-	Y	Y	Y	Y	Y	Y	-	Y	Y	-	-
WOFPH - Left	-	Y	Y	Y	-	-	-	Y	Y	Y	S	Y	Y	-	Y	Y	-	-
WOFP- Vertical	-	Y	Y	S	-	-	-	Y	Y	Y	N	Y	Y	-	Y	Y	-	-
Work Object Rotation	-	Y	Y	Y	-	-	-	Y	Y	Y	Y	Y	Y	N	Y	Y	-	-
Stitch Completed?	N	Y	Y	Y	N	N	N	Y	N	Y	Y	Y	Y	N	Y	Y	N	N

Axis Name	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	Axis Success %
Hook Translation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	98.59 %
Hook Rotation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	S	S	97.18 %
Yarn Wrapper	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	92.86 %
Stitch Lift Solenoid	Y	N	N	N	Y	N	Y	N	N	Y	S	Y	S	S	Y	S	S	71.43 %
Stitch Lift Servo	Y	N	N	N	Y	N	Y	N	N	Y	S	Y	S	S	Y	S	S	71.43 %
Hook Loop Push Servo	Y	-	-	-	Y	-	Y	-	-	Y	-	Y	-	-	Y	Y	Y	97.5 %
Yarn Pull Servo	Y	-	-	-	Y	-	Y	-	-	Y	-	Y	-	-	Y	Y	Y	100 %
WOFPH - Right	Y	-	-	-	Y	-	Y	-	-	Y	-	Y	-	-	Y	Y	Y	92.68 %
WOFPH - Left	Y	-	-	-	Y	-	Y	-	-	Y	-	Y	-	-	Y	Y	Y	97.56 %
WOFP- Vertical	Y	-	-	-	Y	-	Y	-	-	Y	-	Y	-	-	Y	Y	Y	97.56 %
Work Object Rotation	Y	-	-	-	Y	-	Y	-	-	Y	N	Y	N	-	Y	Y	Y	90.24 %
Stitch Completed?	Y	N	N	N	Y	N	Y	N	N	Y	N	Y	N	N	Y	Y	Y	Overall: 50.7%

Legend				
	Null	Semi-Complete	Complete	Not Complete

Fig. 9. The results of the comprehensive single crochet testing. The table keeps track of the success of each axis, each stitch, and the overall success rates of the stitches and the axes. Blue indicates a success, white indicates a success with some minor issue, pink indicates a failure, and grey indicates that the axis did not run due to stitch failure. The success rates for each axis are recorded at the bottom of the chart, as well as the overall stitch success rate.

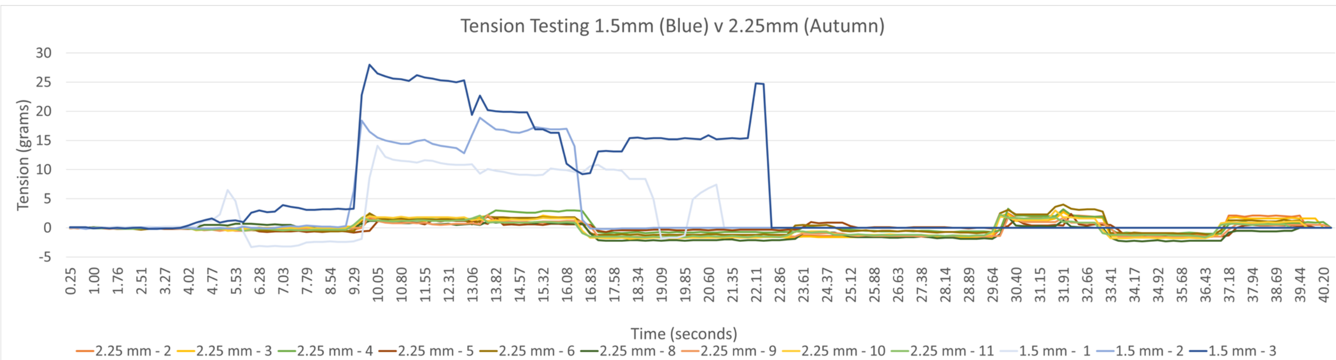

Fig. 10. A graph displaying the tension data from the 1.5 mm (least successful) and 2.25 mm (most successful) tension tests. The amount of tension in the system during the 1.5 mm tests was too great (14 - 28 grams) and caused the machine to stall before completing the stitch. The most successful tests (2.25 mm holes) had a much smaller amount of tension in the system, maxing out at about 4 grams.

stitches the machine completed before an axis failure was four single crochets.

The success rate of each mechanical axis:

- Hook Translation - 98.59%
- Hook Rotation - 97.18%
- Hook Loop Push - 97.5%
- Yarn Wrapper - 92.86%
- Yarn Pull - 100%
- Stitch Insert / Lift - 71.42%
- Work Object Fabric Push Horizontal - 95.12%
- Work Object Fabric Push Vertical - 97.56%
- Work Object Rotation - 90.24%

The most common reason for stitch failure at the start of the stitch was the stitch lift axis missing the stitch or not lifting the working stitch high enough because the crochet fabric was too loose. The stitch lift axis has the lowest success rate at 71.42%. Many of the axis failures that occurred during testing were the result of the flexible nature of the crochet object. The crochet work object, after several stitches, would get bunched up in the work object rotation gears, causing the motors to stall. The crochet work object would also get stuck on the stitch stabilizers or the fabric push axes.

Outside of the single crochet testing, the chain, increase, and decrease motion sequence programs were developed after the success of consecutive single crochet stitches. These motion sequence programs were tested and refined until the Croche-Matic successfully completed one of each stitch type.

V. Conclusion

The machine has successfully completed three consecutive chain stitches, four consecutive single crochet stitches, one increase stitch, and one decrease stitch. This demonstrates that the machine can complete all of the necessary stitches in Magic Ring technique. The machine was able to complete 36 single crochet stitches (three rounds of 12 stitches) within 71 attempts, a 50.7% success rate. This demonstrates that the machine is capable of generating 3D cylindrical geometry, which has not been previously demonstrated with existing crochet machines.

Future work on Croche-Matic will include additional prototyping to improve the overall consistency of the mechanical axes. The increase and decrease stitch programming will be further refined and tested to expand the machine's stitch capabilities. We also plan to integrate computer vision for stitch detection in order to better position the axes to complete crochet stitches in the correct base stitch location. Crochet has over a hundred different stitch types outside of the four stitches demonstrated by the Croche-Matic. There is potential for more stitches to be converted into motion sequence programs and tested in the Croche-Matic. A further goal is to build an interface for the machines where users can input crochet pattern instructions with stitch abbreviations and then the Croche-Matic will be able to produce a complete three-dimensional crochet object on demand.

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