Design of a Prototype Machine to Automate Satellite Wire Harness Assembly

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Abstract
Wire harness construction is a frequent source of delays in the satellite assembly process, due to a high rate of human error in the harness assembly process. While automated assembly could reduce the error rate and increase production efficiency, manipulation of wires with established robotic assembly methods is difficult because of their flexibility. This project introduces a novel machine to automate wire harness assembly by adopting a design similar to that of existing cartesian 3D printers, circumventing problems faced by established automation methods. The machine can rout wire onto a flat wire harness template and can cut and process up to eight different types of wire simultaneously, all without human interaction. This report details the conceptualization and design of such a machine, as well as the current assembly and validation status of the existing prototype. Although the prototype is incomplete at the closing of the 2020 MDP project cycle, it is concluded that the team's current approach shows promise in successfully automating wire harness assembly and should be explored and refined further in future efforts.

Keywords: Automated Wire Handling, Embedded Systems, Gcode, Hardware Design, Wire Processing

I. Introduction

A. Background and Motivation

A wire harness, broadly speaking, is a bundled assembly of insulated cables and connectors that transmits signals and electrical power within a larger system. Individual cables within a harness are bound together tightly, which not only serves to organize electrical connections, but to protect the harness from the harmful effects of vibrations. As such, almost all modern aircraft, spacecraft, and motor vehicles employ these harnesses in their electrical systems.

Construction of the wire harness is one of the most difficult and time-consuming segments of the satellite assembly process. The wire harness of a satellite, in particular, must be especially robust, as satellite platforms generally cannot be maintained at all once launched into orbit. Due to the difficulty of manipulating flexible wires with established robotic assembly systems, such as those commonly used in automotive assembly, almost all wire harnesses across the industry are still constructed by hand. The complexity of these harnesses, combined with the strict standards required for use in satellites [3], results in a relatively high defect rate due to human error. Despite this high error rate, manual assembly has historically still proven to be more cost-effective than automation; this is because of the reliance of previous automation efforts on expensive computer vision solutions and complex robotic manipulators [4]. Nevertheless, if harness assembly could be

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successfully automated, it would have the potential to increase production efficiency and decrease producer business expenses by significantly reducing the harness defect rate.

B. Problem Statement

The goal of this project as described by our sponsor, Northrop Grumman Tactical Space Systems, is to develop a machine to automate the wire harness production process while avoiding the pitfalls of past automation efforts. There currently exists no commercial product that can accomplish this goal as-is [5]. Specific tasks within the harness assembly process for which the machine would be responsible are as follows:

1. Wire prep. operation: *cutting and labeling*
2. Pre-routing wire operation: *stripping, crimping, and terminating into connectors*
3. Routing operation: *routing wire harness on a mockup*
4. Post-routing wire operation: *terminating remaining wires into connectors*

In addition, all cables in our final harness must comply with the workmanship requirements set forth by the relevant NASA technical standard [3]. Ultimately, our machine must be able to take the layout of a wire harness as an input and subsequently output a fully assembled wire harness, which may be transferred directly to an actual satellite. The specific sample wire harness provided to our team by Northrop Grumman is shown in Fig. 1 directly below.

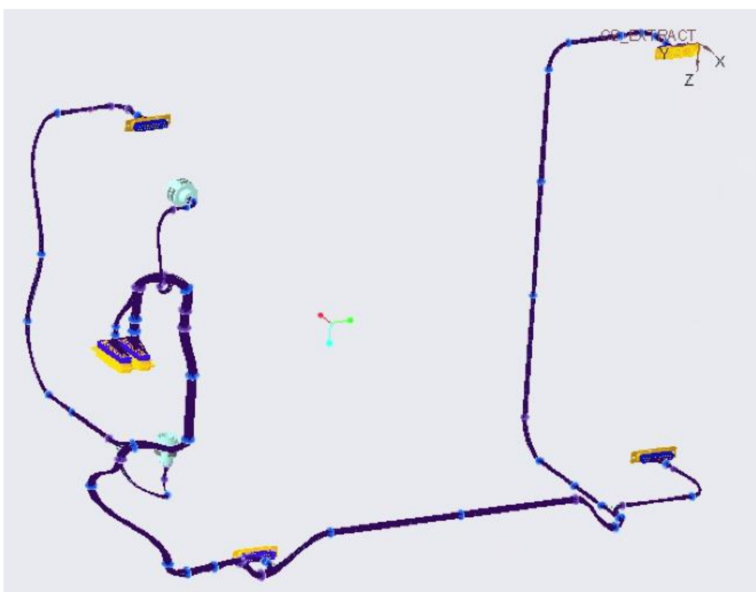

Fig. 1 Isometric view of provided sample wire harness. The sample harness contains many challenging harness geometry features and various example connector shapes.

Due to unavoidable delays to the work schedule caused by the 2020 COVID-19 lockdown, many secondary or stretch requirements of the machine prototype were reevaluated and dropped over the course of the project. These requirements included the ability to accommodate coaxial, shielded, and twisted pair cables, as well as the wire crimping, labeling, termination, and bundling operations. Instead, as a compromise, these difficult-to-automate tasks would be temporarily assigned to a human operator for testing and validation of the other subsystems, while space would be left in the design for eventual expansion by the project successors. The primary requirement for the machine was subsequently redefined as simply the validation of routing functionality.

II. Design Approach

A. Literature Review

Prior to beginning design work, a literature review was conducted to improve team understanding of wire processing and assembly automation, and to help determine whether the assigned project was feasible to accomplish within the period of our involvement. Through this literature review, it was discovered that many of the wire operations the machine was expected to accommodate had already well-established methods of automation [2,5]. Commercial automation solutions for wire prep operations such as cutting, stripping, and crimping are both commonplace and readily available. Conversely, other processes such as wire routing, bundling, and connector termination are ill-suited for automation, and may require more complex solutions. In particular, manipulating and routing wires in 3D space is challenging in that it cannot rely on standard motion playback, and is an active area of research [1]. From the results of this literature review, the team concluded that a machine as specified by our sponsors was feasible based on existing technology. While automated wire routing was expected to be a challenge, it was determined that it would be achievable if the problems with wire manipulation in 3D could be circumvented.

A second literature review was conducted prior to the start of design work on the cutting and stripping subsystems, to develop a deeper understanding of these specific operations. This review focused on patents and existing commercial products that serve these purposes. Based on existing commercial products, it was concluded that an efficient way of processing each wire was to place the processing machine in the flow of the wire from the spool to the workspace [6]. A bi-directional cutting and stripping method using a lead screw was also adopted based on several patents of similar machines [2], to ensure the alignment and precision of the cutting blades. This method would allow the machine to strip multiple wire sizes using the same blade, by controlling the blade separation when fully closed. Although existing machines and standalone units were notably bulky, it was determined that it would be feasible to miniaturize and integrate a wire processing unit operating on these principles into the final cutting and stripping machine.

B. Design Concept

The high-level design concept of the machine was based on the design of existing FDM 3D printers. Just as a 3D printer extrudes plastic filament layer-by-layer onto a hotbed to build up a plastic component, the wire harness machine would lay down wire onto a workspace to create the layout of the harness. However, while the base functionality of the machine is similar to that of 3D printers, the design of wire harness machine faces various additional challenges. One such challenge includes the requirement to cut and process, i.e., strip and crimp, each wire prior to the main routing operation. Because the final length of each wire will vary through bends and curves based on their relative location within the bundle, the cutting and processing operations must be independent of variations in length, thus ruling out the cutting of wires ahead of time and requiring the processing functionality to be integrated into the machine itself. In addition, the machine must be able to accommodate many different wire gauges and types and must be able to switch between them on-the-fly. This requires multiple wire spools to be stored on or near the machine and for each to be fed and retracted automatically as required.

The wires are cut and processed while in transit to the workspace. This final order of wire processing operations was established relatively late in the design phase, following the completion of the second literature review. It was determined that all wire processing operations would be carried out continuously at a location upstream of the wire path to the extruder, rather than after the routing operation or as part of a separate tool head. Both ends of the wire are processed in sequence without the need to flip the wire around. This method minimizes the time the wire is unsupported, which circumvents the problems associated with wire manipulation as described above and avoids excess downtime for tool changes or repositioning.

Once the wire has been cut and processed, it may then be routed into place. The primary routing operation relies on the coordinated motion of the machine tool head, which contains the extruder, and the extruder motor itself. The motion of each of these components is controlled by a TinyG CNC motion controller board. As the tool head moves through the input wire path, the extruder lays down wire at roughly the same linear speed, allowing the wire to fall into place. Of note is that the harness will be initially routed as a 2D pattern, and then folded into the final 3D shape of the harness after completion. Although this decision creates more work to unfold the design of the harness in software and requires additional slack to be added to unfolded bends, it greatly simplifies the design of the rest of the machine. A visualization of the harness unfolding process is shown in Fig. 1 below, which also demonstrates that there are multiple ways in which a single wire harness may be unfolded.

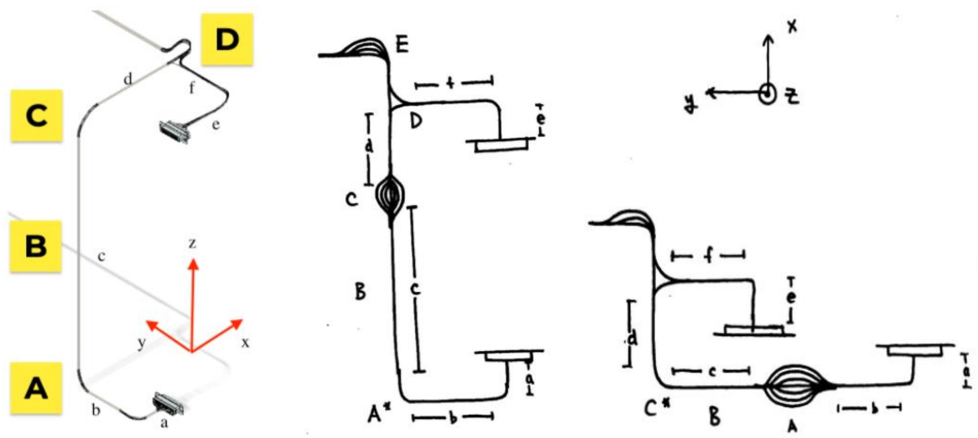

Fig. 2 Illustration of a wire harness section (left) and two equivalent, unfolded sections (center & right). Analogous bends between them are labeled.

During the routing process, the wire will be held down on the workspace using a variety of 3D-printed clips. The clips are designed to be adjustable both in location and orientation angle and will be secured to a pegboard or optical table, as required by the harness design. There are four distinct varieties of clips, each of which would serve a distinct purpose:

1. *Round* clips, with a single opening at the top, would guide the path of the wire bundle in both bends and straight sections and maintain the shape of the bundle.

2. *Comb* clips, with multiple smooth slots, would separate wires and allow the necessary slack for bends in the 2D harness state.

3. *Cactus* clips, with multiple serrated slots, would hold wire ends in the correct position to be inserted into a connector housing.

4. *Active* clips, which would be opened and closed with an actuator, would securely hold wire ends during the routing operation to maintain tension.

To account for variable wire lengths due to location in the bundle, an integrated tension sensor in the tool head would measure the tension of the wire as it was extruded, allowing feedback control to maintain a desired tension level. Once all wires have been extruded, the bundle may be removed from the clips, refolded and untwisted as necessary, and laced or tied to form the final wire harness. The four types of clips are illustrated in Fig. 3 below.

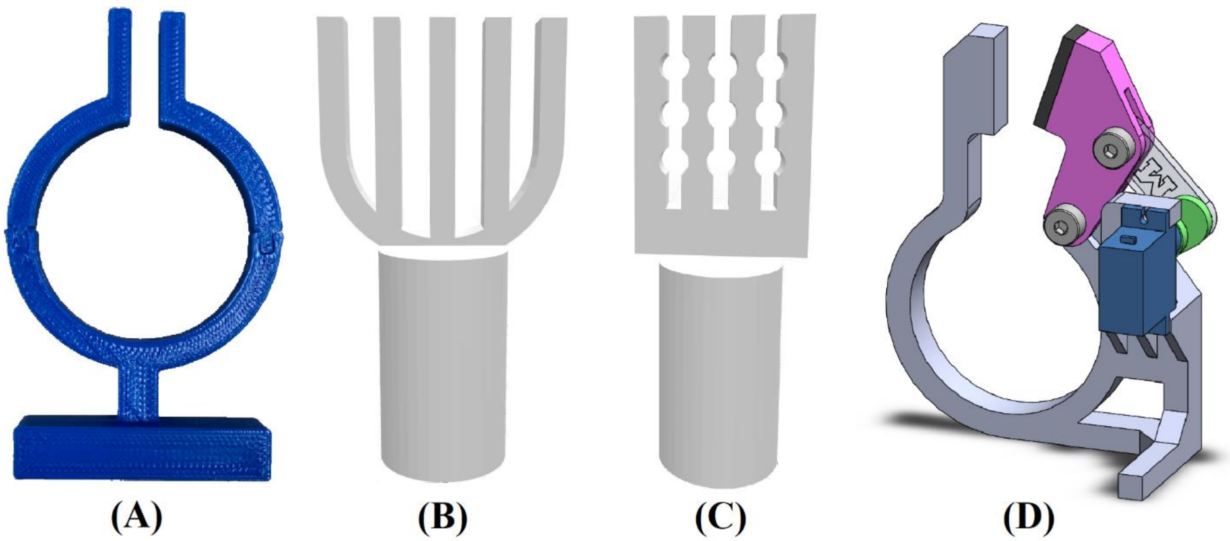

Fig. 3 All wire clip designs. From left to right: round clip (A), comb clip (B), cactus clip (C), active clip with micro servo (D).

C. Preliminary Design

The initial design responsibilities of the machine prototype were divided amongst the team, with one group working on the mechanical design of the machine, and another working on embedded software and algorithms. In addition, members from both groups contributed to the development of the harness routing strategy and the determination of the final wire processing order of operations. Once the design of the prototype machine developed further over the course of the winter and summer, the team restructured into more subsystem-focused groups for the fall.

On the software side of the project, preliminary work focused on converting the PTC Creo harness CAD file supplied by the sponsor to a format that could be used as a machine input. Wire harness geometry was extracted from the CAD file and used to determine the path of the bundle centerline through the entirety of the harness. The number and gauge of wires in each harness branch were then used to determine an estimate of bundle size based on a generalized packing density factor, which was then to be used to calculate an offset for wire placement within the bundle. Other preliminary work sought to automatically determine clip placement locations based on the bundle centerline and its curvature, while also dynamically scaling clips based on local bundle size as described. However, unexpected setbacks in extracting centerline data from the CAD meant that software progress was delayed significantly until the end of the first semester. Later software work sought to automate and optimize unfolding and twisting of the sample wire harness into 2D by identifying bends in the harness geometry, although initial unfolding attempts were carried out manually to aid in the validation process.

On the hardware side, most of the preliminary design of the prototype was completed and finalized remotely over the summer period, carried out almost exclusively in SolidWorks CAD. Physical validation and prototyping of designs were extremely limited during this phase due to lack of lab access; prototyping did not begin until the start of the Fall 2020 semester, and the return of the team to the university campus. The mechanical design of the machine itself was broken down into five major subsystems:

1. Wire Extruder Tool Head

2. 3-Axis Translation Stage

3. Wire Switcher/Selector Unit

4. Cutting and Stripping Unit

5. Passive and Active Clips

An illustration of the prototype machine with each of these major subsystems numbered as above is shown in Fig. 2 below. Additionally, the design and functionality of each subsystem are explained in detail in subsequent sections.

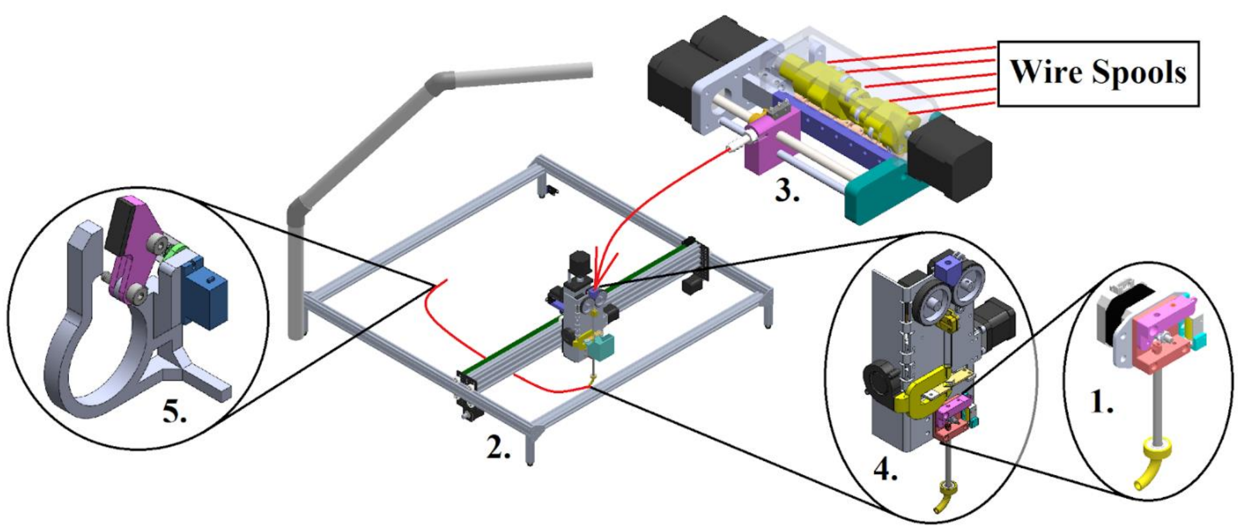

Fig. 2 Diagram of complete routing machine with critical subsystems labeled.

1. Wire Extruder Tool Head

The main body of the wire extruder was borrowed from a commercially available 3D printer filament extruder, and functions in much the same way. The central drive gear of the extruder, however, has been replaced with a rubber drive roller so that the extruder action does not damage the wire insulation. This is a requirement specified by the NASA workmanship standard. As intended, the extruder is driven by a single NEMA 17 motor and is rigidly attached to the face plate of the cutting and stripping unit to which its wire path is coupled. An additional actuator, a pull-type solenoid, was originally included in the design to actuate the lever that disengages the roller idler bearing, allowing a new wire to be loaded in. This solenoid, however, has not been integrate or tested in the current prototype configuration due to time constraints.

The tube at the exit of the extruder, along with two orthogonal strain gauges mounted on the left and front of the tube, comprise both the extruder output and tension sensor mechanism. As the wire exits the tube and is secured by the clips located on the workspace, a tension force is applied by the wire approximately to the bottom of the tube exit, causing a strain at the gauge location due to bending. These strains can be measured using the orthogonal strain gauges and used to calculate the tension force in the wire using the known geometry of the tube. Subsequently, this tension measurement can be used in a feedback controller regulating the wire tension; this can ensure both that the wire does not have excessive slack on the workspace, and that excessive force is not applied to the wire as to stretch and damage it. While the strain gauges have been selected, calibration and testing has not been completed. Multiple versions of the tube are currently being considered, including a stiffer aluminum tube and a more flexible polymer tube, from which a final selection will be made based on the expected tension force and strain gauge readings.

The final component of the extruder assembly, the 90-degree elbow tube at the exit of the tube, is mounted on a bearing and spins freely. This guide tube maintains bend radius of the wire at the minimum expected value for the gauges of wire the machine is designed to accommodate and allows the wire to exit the extruder assembly parallel to the work surface. Finally, the free-spinning bearing mount allows the exiting wire to trail the tool head opposite of its direction of motion, though it must be aligned at first through an external guide, such as an open clip. A close-up of the entire extruder assembly is shown in Fig. 3 below.

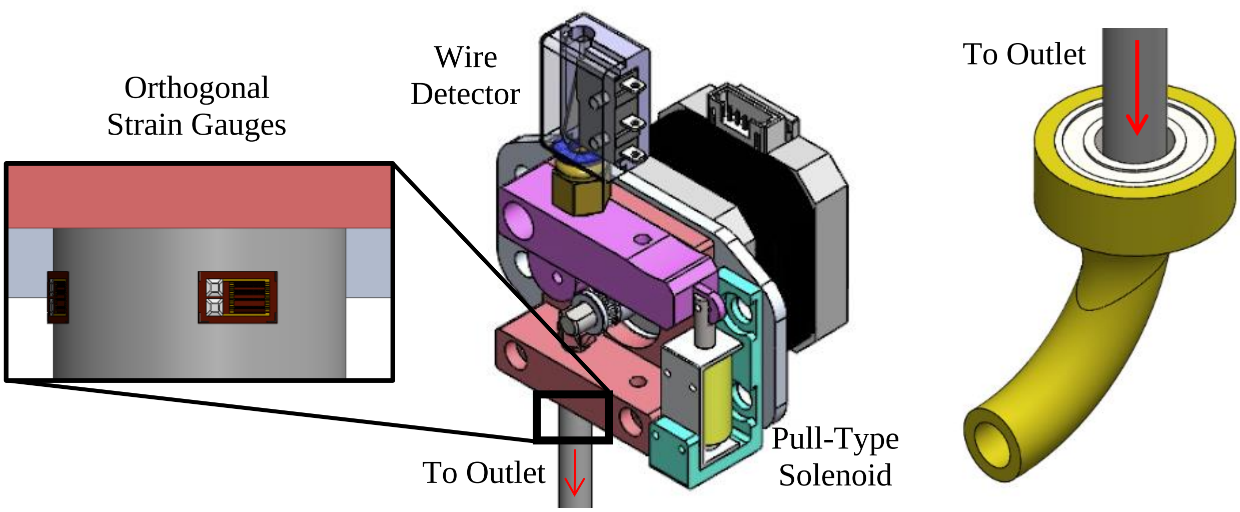

Fig. 3 Detailed view of extruder assembly. *Left*: close-up of strain gauges showing orthogonal placement on left and front sides. *Right*: curved wire guide with bearing mount.

2. 3-Axis Translation Stage

The general structure of the translation stage was based on existing CNC machine designs with similar motion capabilities. Following a standard right-handed coordinate system, the machine is capable of independent motion in the x, y, and z axes with separate actuators in each direction. A lead screw actuator was selected for the machine z-axis, making use of a readily available kit from open-source CNC hardware supplier OpenBuilds. This selection satisfied the design requirement for the machine to hold its position during a power failure, so as not to damage previously routed wires, as the single-start lead screw resisted being back-driven by gravity. Meanwhile, a belt-and-pinion system was selected for both the machine x and y axes, where speed was more of a concern. This system offers faster motion compared to the lead screw z-axis and is easily adjustable and expandable. In addition, by mounting the x and y motors to their corresponding gantry carts, the unusable space at the end of each axis was minimized, allowing the machine to make the best possible use of its 1000 mm by 1000 mm footprint and accommodate larger unfolded harnesses. Like the z-axis, the remainder of the translation stage also made use of OpenBuilds components albeit in a clean-sheet design. The machine is shown in Fig. 2, on pg. 6.

The translation stage of the machine is currently controlled by a single TinyG motion controller. A TinyG board has a total of four stepper motor drivers, which allows each axis of the machine plus the extruder motor to be driven independently, though the y-axis in reality uses two motors wired in series due to its large width. Eventually the motion of the extruder motor will instead be controlled by a secondary TinyG board, to synchronize its motion with other motors in the wire processing unit; it is less critical for the extruder motor motion to be strictly synchronized with the translation stage, as feedback control based on the tension sensor will be used to control the motor feed rate instead. A diagram of the complete embedded systems structure of the machine may be found in Fig. 7 on page 12.

3. Wire Switcher Unit

The automated wire switcher unit was based on similar designs used for 3D printers capable of multi-filament printing. Like these designs, the wire switcher is capable of preloading multiple different types of wire, in this case up to eight, and selecting a single wire to feed during operation. This selected wire exits the wire switcher through a single shared exit tube, which guides the wire to the extruder. An image of the final wire switcher design is shown in Fig. 4 below.

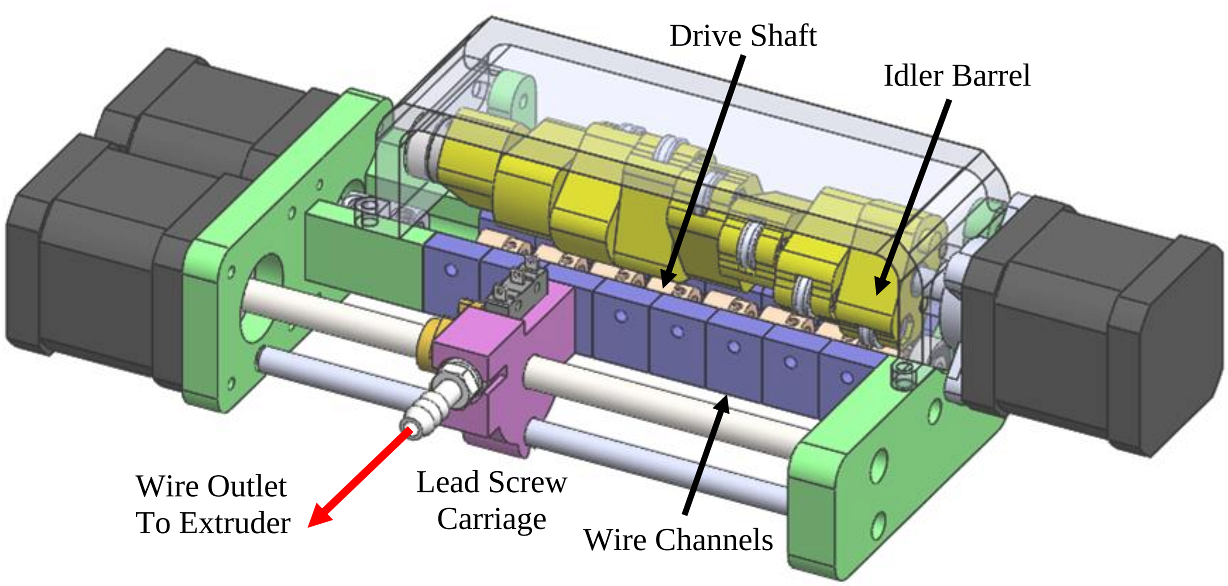

Fig. 4 Detailed view of wire switcher assembly.

When not in use, each wire rests in an individual guide channel and is not engaged by the shared main drive shaft. Subsequently, when a wire is selected, the idler barrel rotates so that the wire is engaged by the drive shaft through its corresponding idler bearing. The lead screw on the outlet side brings the selector carriage to the exit of the wire channel, and the wire is driven through the outlet tube, where it engages a sensor to indicate that it has passed through. Both the wire channel and idler barrel are modular; each segment of these structures can be configured to accommodate a specific gauge of wire or a specific cable type. Segments are joined together using bolts, allowing for individual pieces to be easily swapped out. This modularity is made possible by the extensive 3D printed construction of the wire switcher, which allows variations of each component to be manufactured quickly and easily.

The process of changing wires is an interesting challenge for the wire switcher due to the great distance between the outlet of the wire switcher and the inlet of the tool head, which may be over one meter in distance due to the footprint and range of motion of the translation stage. This great distance means that each wire must be carefully retracted prior to engaging another wire and made to rest exactly at the edge of the wire channel. Additional sensors may be required in future design revisions to ensure this alignment.

4. Cutting and Stripping Unit

The design of the wire cut/strip unit was influenced by the conclusions drawn from the second literature review. Based on several existing commercial products, three major components of the system were identified: inlet and outlet side drive rollers, opposing cutting blades, and a central pivoting wire guide. While these features were common among commercial cut/strip units, a custom, miniaturized design was warranted, so that the unit may be integrated into the machine tool head and move with the extruder. Doing so would allow the machine to accommodate shorter wires by minimizing the distance between the processing rollers and the extruder. An image of the final cut/strip unit design is shown in Fig. 5 below.

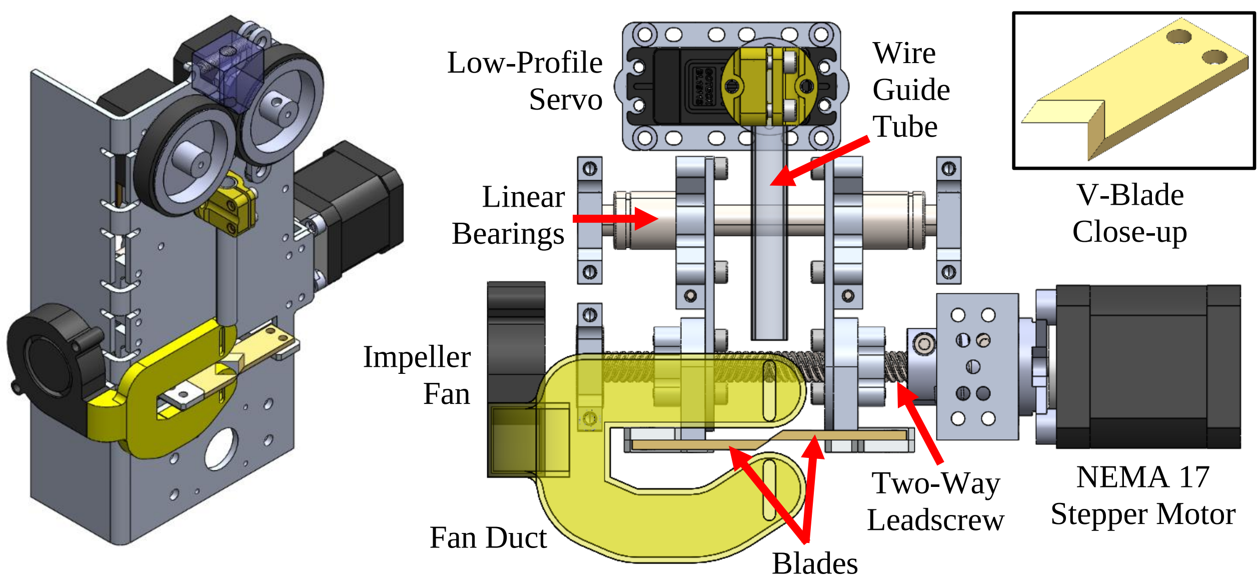

Fig. 5 *Left*: complete view of cut/strip unit without extruder assembly. *Right*: view of cutter and wire guide subsystems with rigid face plate removed.

The location of drive rollers on either side of the blade allowed both ends of the wire to be processed without flipping. The inlet-side drive rollers consisted of two wheels with a high-friction tread to grip the wire insulation and are driven by one NEMA 17 each. These motors were selected based on measurements of stripping force obtained from sample wires, which were used to calculate the torque requirement based on the minimum spacing of the motors. In turn, the wheels themselves were sized based on the motor spacing to minimize the unsupported distance from the rollers to the wire guide, which was determined in CAD. To accommodate a larger range of wire sizes, the right-side roller and motor is mounted on a pivoting linkage so that the space between the two rollers is variable. Clamping force between the two sides is then maintained through a tension spring between the rollers. Meanwhile, the role of the outlet-side drive rollers is currently served by the extruder gear and idler, which engage the wire after the cutting blades. While this substitution seems to be reasonable, independent outlet-side drive rollers may eventually replace the extruder entirely to better match the feed rate between the inlet and outlet.

Next, the wire guide, located between the inlet-side rollers and the cutting blade, consists of a small metal tube attached to a servo. The length of this tube is determined by the size of the blade mechanism, which is unavoidable due to the layout of the miniaturized system. Meanwhile, the servo allows the tube to pivot slightly in the plane of the cut/strip unit faceplate. Thus, when the rear end of the wire is being stripped, this pivoting action allows the free end of the wire to move out of the way of the stripping operation without needing to retract. Because of the large distance between the wire switcher and the cut/strip unit, any retraction operation will be relatively time-consuming and undesirable during extended operations.

Lastly, the blade subsystem, with just a single set of opposing V-shaped blades, is able to both cut wires and strip their insulation based on the level of blade closure. The two blades are mechanically linked so that their motion is mirrored across the wire centerline; each side is driven using a lead screw on the same axis, but of opposite handedness, resulting in opposing linear motion when the screw is turned in one direction. The screw itself is driven using a single NEMA 17 stepper motor, which allows the distance between the blades to be precisely controlled when calibrated using a limit switch. To guarantee the precision of the blade subsystem, a very stiff faceplate was chosen for the cut/strip unit and the blade subsystem itself was constructed almost entirely from off-the-shelf or machined metal components.

One added functionality of the cut/strip unit is the addition of a blower fan and fan duct. Because of the vertical orientation of the unit, stripped insulation will tend to fall downwards through the blades and into the workspace. The purpose of the fan is thus to produce an air jet facing away from the face plate to blast pieces of stripped insulation sideways, whereupon the pieces would be collected in a receptacle attachment. As an additional note, while the wire processing unit was originally intended to include the additional capabilities of connector crimping and labeling, these processes were deemed too challenging in the timeframe allotted and were not realized during the project period. It is left up to the following team to build upon the prototype design to integrate these operations.

5. Active Clips

As mentioned in the design concept section, the purpose of the active clips is to secure the ends of each wire, but only during the routing process. As such, it was necessary for the active clip only to hold one wire end at once, after which it could be released. The design of the active clip allows this single wire fixturing by placing an actuated clamp vertically above a circular wire reservoir, so that after the wire end is released by the active clip, it simply falls and is collected in the circular portion. The clamp of the active clip is driven by a change-point linkage, so that no significant torque is required from the servo to maintain the completely closed position. The servo itself is controlled directly by the Raspberry Pi through a 16-channel servo controller, which is sufficient for the number of clips required for the sample harness application. Like the wire switcher, the active clips are almost entirely 3D printed, enabling easy scaling and modifications to clip geometry, as necessary. The active clip is shown in Fig. 2, on pg. 6.

6. Embedded Systems

The functions of each of the individual subsystems of the prototype machine are united and coordinated through custom embedded systems, essentially allowing the machine to function as one cohesive system. Currently, three individual TinyG CNC Controllers are used to drive all the motors between the machine translation stage, the tool head, and the wire switcher. As is typical of many CNC applications, TinyG is programmed using *Gcode*, which may be directly translated into machine motions. Figure X below depicts the model of TinyG board used in the prototype.

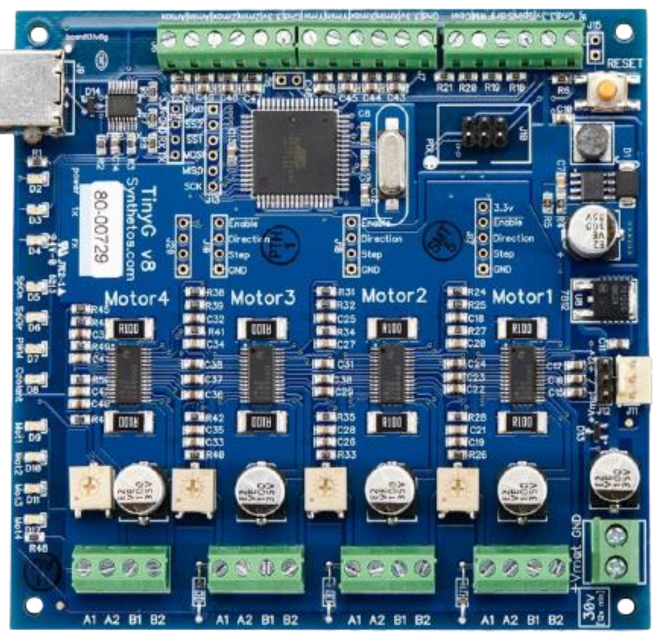

Fig. 6 Representative TinyG CNC controller board with four separate motor drivers.

While these boards are not able to communicate with one another directly, their actions can be coordinated by coordinating the Gcode received board. This is accomplished through *Chilipeppr,* an open-source Gcode sender. Chilipeppr functions as the *publisher* in the Gcode publish-subscribe pattern; sent Gcode is differentiated between commands intended for the translation stage, tool head, and wire switcher, and are acted upon in sequence by the three subscriber TinyG boards. The resulting system allows all three TinyG boards to coordinate their actions, although it is still preferable to keep actions that must be precisely synchronized together on the same board. A diagram of the embedded systems architecture for the prototype machine is shown in Fig. 7 on the following page.

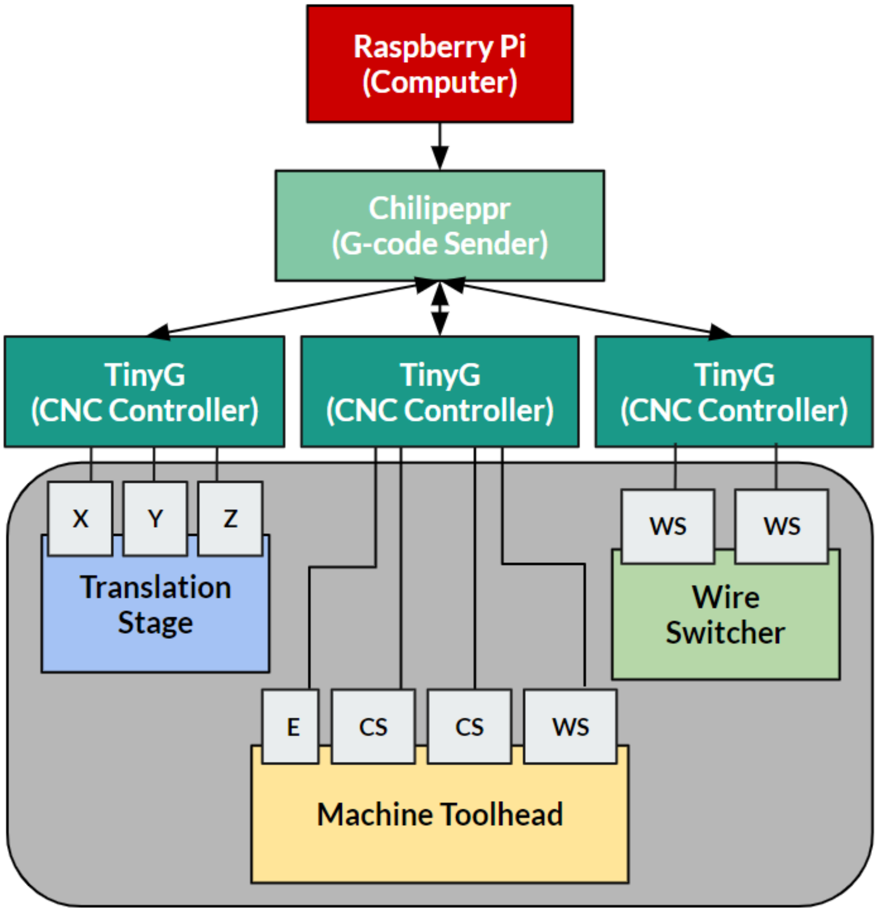

Fig. 7 Embedded systems architecture diagram. In the Machine Toolhead and Wire Switcher blocks, *E* represents extruder motion, *CS* represents cut/strip motion, and *WS* represents wire switcher subsystem motion.

III. Design Validation Methods

Validation of the preliminary machine design was carried out starting the Fall 2020 semester. Assembly of the translation stage began in September and was completed in October, while assembly of the wire switcher and extruder continued through November. Assembly of the cut/strip subsystem, for which the required off-the-shelf components were received late into the semester, was not yet complete by the end of the November but was eventually finished during the winter break period. Because the prototype machine had not been completed before the end of the semester, not all the subsystem designs were able to be validated by the project completion date.

The primary focus of the design validation was shifted away from the production of the supplied sample harness to a simpler, student-defined demonstration harness. This was because even though the software team had been able to extract the wire centerline data by the time of testing, neither the functionality to use that data as an input to the machine nor the algorithm to unfold and flatten the harness pattern had been fully implemented. However, the machine had demonstrated that it was capable of motion in all 3 axes and had been calibrated using the built-in functionality in TinyG. Instead of following the supplied sample harness pattern exactly, the demonstration harness intended to test and show off all the various motions that would be expected from the machine. This included continuous bends, unfolded bends, untwisted straights, and changes in elevation. Emphasis was placed on the demonstration of automated routing, as this was the one process identified both by our team and by Northrop Grumman as the most difficult and least understood automation challenge. Additionally, because neither the wire switcher nor the cut/strip subsystems had been completed prior to the start of testing, neither was included in the demo harness test. The harness path was marked on the pegboard and clips were set, as necessary. The pattern used is shown in Fig. 8 below, along with the Chilipeppr Gcode GUI used for testing.

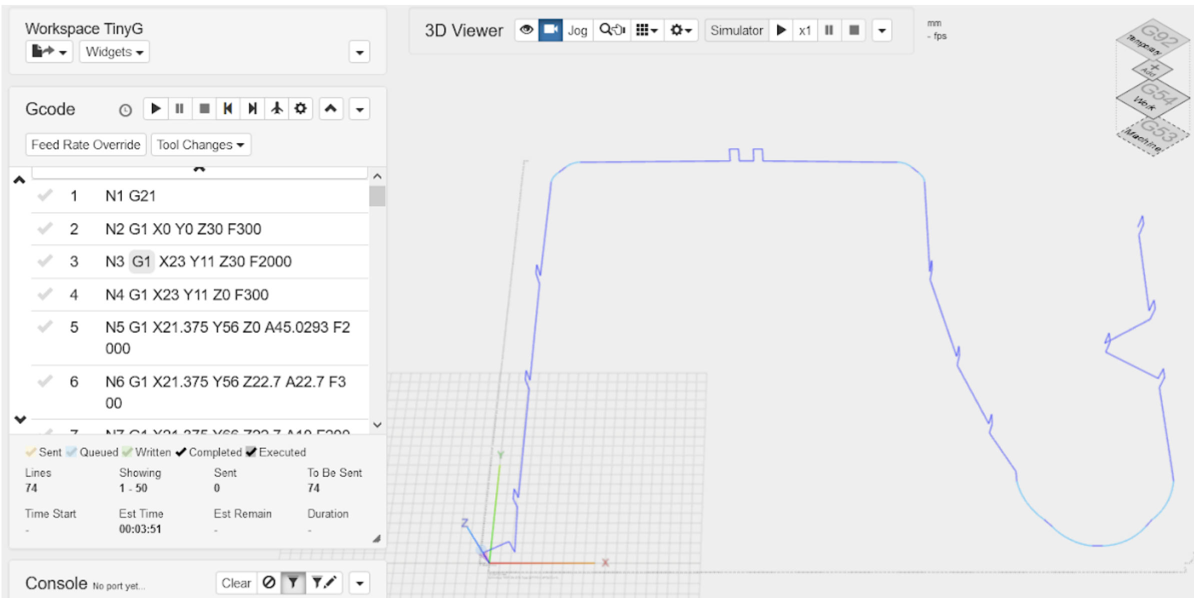

Fig. 8 Demonstration wire harness centerline path, shown in blue. Routing begins at the origin. Gcode for the harness path is shown in the left of the Chilipeppr window.

After the clips had been installed, measurements of the clip coordinates and angle were taken by hand in relation to the machine origin. These coordinates were used as guide points for the machine wire path. Using these points, as Gcode representation of the wire path was manually transcribed into Chilipeppr, resulting in the harness pattern above. Each vertical kink in the harness path represents the presence of a clip, where the machine goes through a clip insertion motion to bring the wire over and down into the clip opening. Because feedback control had not yet been implemented, the extruder feed rate was instead calibrated to be the same as the machine horizontal feed rate at each segment.

Several other items were validated independently of the machine, including the photosensors used for wire detection and active clips functionality. Photosensor functionality was verified using an existing Arduino implementation. Once the sensor was operational, different types of common wire insulation were tested against a brushed aluminum plate. Voltage measurements were recorded for each material, and a functional range was determined based on identified threshold voltages. Meanwhile, active clips were tested using an existing servo driver. Servo functionality was confirmed, and commands for fully open and fully closed positions were determined. Practical tests were performed on wire segments simulating tension during routing. However, the precise holding force of the active clips was not measured.

IV. Results and Discussion

The machine successfully routed the demonstration harness, showing that the translation machine was able to follow the wire path to a high degree of accuracy when controlled through TinyG and Chilipeppr. This result is promising as it proves the feasibility of the main concept of the machine. A top view of a nearly completed demonstration harness is shown in Fig. 9 below.

Fig. 9 Overhead view of completed demonstration harness showing various clip designs and clip placements. The extruder tube may be seen in the top right corner.

Unfortunately, most of the prototype subsystems and machine components have yet to be satisfactorily tested as of the end of the semester. Supplier delays and the compressed project time frame meant that the team was not able to complete nearly as much testing as originally planned. For example, while the action of the extruder was proven to work during the demonstration harness test, the tension sensor was not used as the required amplifier circuits to use the strain gauges had not been constructed. Instead, the matching of the extruder feed rate with the horizontal feed rate relied on a lengthy calibration process and resulted in the wire having *no* tension during routing. While this feedforward method allowed the demonstration harness to be completed, the results were less than ideal as proper tension was not maintained, resulting in a loose and poorly secured harness. Furthermore, because wire cutting had to be done manually, the machine translation stage could not be fully evaluated in reliability nor repeatability. These are important variables to be determined in future tests to prove the viability of this design concept.

One component with no testing at all testing is the wire switcher device, though it was partially demonstrated to be functional during handfeeding of wires. The team ran out of time to connect the wire switcher motors to a new TinyG board, and so handfeeding was used to simulate different wires passing through the wire switcher one by one. Similarly, the cut/strip subsystem that was recently completed following design expo has only been tested by hand, using the fingers to turn the leadscrew and rotary shafts, as the author does not have access to a TinyG CNC controller nor a power supply while off-campus. The wire switcher demo and routing machine sans cut/strip setups used for the demonstration harness are shown in Fig. 10 below.

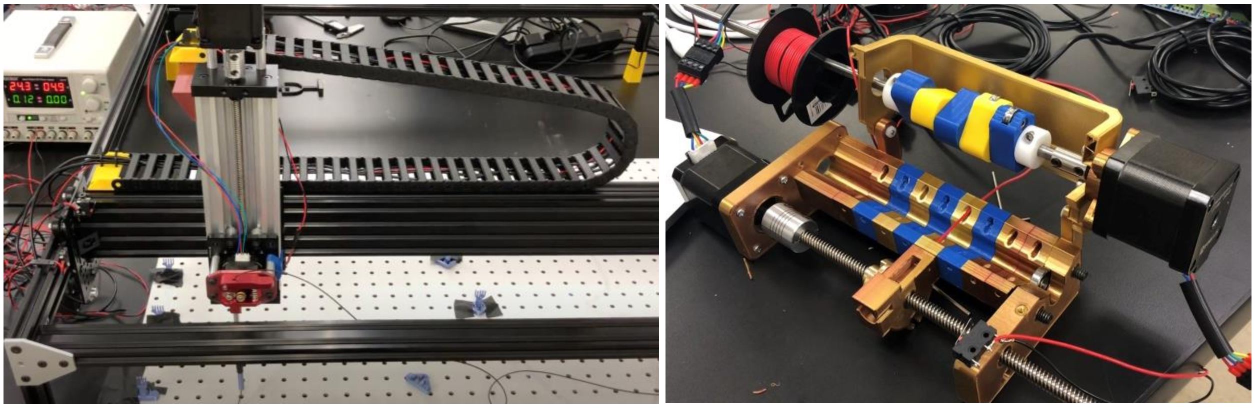

Fig. 10 *Left*: Machine configuration used for demonstration harness routing with extruder attached directly to z-axis carriage. *Right*: Unpowered wire switcher demo configuration with missing drive shaft and reduced wire capacity due to design error.

V. Conclusions and Future Work

While the prototype is currently missing many desirable functionalities, such as automated wire crimping and labeling, the core routing functionality of the machine shows promise. The ability of the prototype to, at the bare minimum, route the demonstration harness, shows that the machine design would be capable of producing a complete harness layout if the embedded controls were refined and the wire processing subsystem would be successfully implemented.

There are some requested functionalities that the team believes will be difficult regardless of the circumstances. For one, automated termination of wire ends into connectors is challenging due to the required precision and the difficulty of manipulating flexible wires and is an ongoing area of research. While these capabilities would be desirable in a future revision of the machine, in its current state it is more pressing to finish and refine the implementations of existing functionalities. The routing algorithms for the translation stage could be greatly improved, and subsystems such as the wire switcher and wire processing unit still are still missing the programming required to function at all. Many designs are even incomplete, missing critical photosensors and limit switches required for operation.

Lastly, several design flaws have been identified in these subsystems during the assembly process, requiring design revisions and potentially even design overhauls from the new team; this is one consequence of designing these components purely through CAD without access to accurate models of each individual component. Further testing is required to confirm the functionality of some of these designs, including validation of the tension sensor strain gauges, and extensive testing of both the automated wire feeding process from the wire switcher to the cut/strip unit and tool head and the retraction process going in the opposite direction.

The author hopes that future iterations on the work completed during this project cycle will help realize the full potential of the automated wire harness assembly machine concept.

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Appendix

A. Wire Harness Nomenclature

Wire	A single metallic conductor of solid, stranded, or tinsel construction, designed to carry currents in an electrical circuit. It may be bare or insulated.
Wire Harness	One or more insulated wires or cables, with or without helical twist; with or without common covering, jacket, or braid; with or without breakouts; assembled with two or more electrical termination devices; and so arranged that, as a unit, it can be assembled and handled as one assembly.
Strip	To remove insulation from a conductor.
Jacket	The outermost layer of insulating material of a cable or harness.
Shielding	The metal covering surrounding one or more conductors in a circuit to prevent interference or signal radiation.
Crimping	The act of physically compressing a contact barrel around a conductor to make an electrical and mechanical connection to the conductor.
Contact, Pin	Male-type contact designed to slip inside a socket contact.
Contact, Socket	Female-type contact designed to slip over a pin contact.
Connector, Body	The main portion of a connector to which contacts and other accessories are attached.
Connector, Grommet	An elastomeric seal used on the cable side of a connector body to seal the connector against contamination and to provide stress relief.
Connector, Insert	The part of a connector that holds the contacts in position and electrically insulates them from each other and the connector body.

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