ACTUATORS AND SENSORS OF A HYBRID SPATIAL CABLE-DRIVEN PARALLEL MANIPULATOR

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ABSTRACT

A parallel manipulator with hybrid actuation is being developed to expand the capabilities of conventional Cable-Driven Parallel Manipulators (CDPMs) by replacing one of the cables with a rigid kinematic chain containing a compact linear actuator. In order to control this manipulator, position and force measurements are made for each of the four actuators (three cables and one extensible linear actuator). The hardware implementation is discussed including sensors, actuators, microcontrollers, and communication methods. This will be completed using ROS2 (Robot Operating System) to help implement a real-time capable control system. The choice of efficient and robust communication methods is discussed for communication between microcontrollers that allows for many messages to be received per second. This will help maintain low latency on the control system, and reduce the chance of missed signals at each point in the communication.

Keywords: mechatronic system; telescoping actuator; cable robot; hybrid actuation.

ACTIONNEURS ET CAPTEURS D'UN MANIPULATEUR PARALLÈLE HYBRIDE SPATIAL ENTRAÎNÉ PAR CÂBLES

RÉSUMÉ

Un manipulateur parallèle d'actionnement hybride est développé pour étendre les capacités des manipulateurs parallèles entraîné par câbles (MPEC) en remplaçant un câble avec un actionneur prismatique compact. Pour contrôler ce manipulateur, la position et la force sont mesurées pour chacun des quatre actionneurs (trois câbles et un actionneur prismatique). La conception physique est discutée à détail, y compris les capteurs, les actionneurs, les microcontrôleurs et les méthodes de communication. Ceci sera complété avec le Robot Operating System (ROS2) pour exécuter une stratégie de contrôle capable de fonctionner en temps réel. La communication robuste et efficace entre les plusieurs microcontrôleurs est discutée. Ceci aidera à maintenir une faible latence et réduire le risque des signaux perdus à chaque moment de la communication.

Mots-clés : système mécatronique ; actionneur prismatique rétractable ; robot parallèle entraîné par câbles ; actionnement hybride.

NOMENCLATURE

A	proximal anchor point
$\mathbf{a}$	vector from global origin $\mathbf{O}$ to anchor point A
B	distal anchor point
$\mathbf{f}$	vector of actuator forces
$\mathbf{J}$	Jacobian matrix
$\mathbf{l}_i$	vector BA
l	magnitude of vector $\mathbf{l}_i$
ω	Resolution of the quadrature encoders ($1\times$, $2\times$, or $4\times$)
ρ	Pulses per revolution of encoders
$\mathbf{r}$	position of end-effector
$\mathbf{u}_i$	unit vector of $\mathbf{l}_i$
$\mathbf{w}_p$	prescribed wrench of the manipulator end-effector
Subscripts	
i	actuator number from 1-4
Acronyms	
ADC	Analog-to-Digital Converter
CDPM	Cable-Driven Parallel Manipulator, cable robot
EE	End-Effector
FDP	Forward Displacement Problem
h-CDPM	Hybrid CDPM
HPRLA	High Packing-Ratio Linear Actuator
IDP	Inverse Displacement Problem
NUC	Next Unit of Computing
QEI	Quadrature Encoder Interface
ROS	Robot Operating System
UART	Universal Asynchronous Receiver-Transmitter
UPS	Universal Prismatic Spherical

1. INTRODUCTION

1.1. Cable-Driven Parallel Manipulators

One developing research area in robotics is the use of cable-driven parallel manipulators (CDPMs or cable robots), which replace the rigid links and joints of standard parallel manipulators with cables kept under tension with winches. This class of manipulator can be seen as an extension of the capabilities of cranes. Since their inception in the 1980s [1] and other foundational works in the area [2], these manipulators have grown in popularity as the computational tools to analyse and control them have significantly improved. This class of manipulator has benefits over rigid-linked parallel manipulators stemming from the lower mass of cables over rigid links, which have been realized with extremely large workspaces, incredibly high accelerations, high degrees of redundancy, and efficient movement [3, 4]. Applications of an extremely large workspace include the Skycam [5], patented in the 1980s and used to film sporting events in stadiums ever since, as well as mechanisms to orient a large reflector for a radio telescope [6].

1.2. Hybrid Linear Actuator

While the efficiency, speed, and workspace size of CDPMs are useful improvements over the capabilities of conventional parallel manipulators, they are statically and dynamically limited by the requirement for constant positive tension in the cables for the manipulator to remain controllable. CDPMs typically require actuators both above and below the workspace in order to have downward forces and accelerations that are not limited by gravity, with the cables pulling against one another antagonistically. Hybrid CDPMs or h-CDPMs refer to CDPMs that use one or more rigid kinematic chains in combination with cables. The h-CDPM studied here is of a special class of h-CDPM that uses an extensible linear actuator that attempts to mimic a cable that can push. This actuator can provide a tensile or compressive force along the line of action of the actuator. The goal of this manipulator is to expand the capabilities of CDPMs with all of the actuators above the workspace to make a pick-and-place manipulator with applications in cluttered industrial workspaces.

Manipulators have used linear actuators to provide compressive forces to help keep the cables under tension since their first inception [1], and similar designs have been used by several other researchers since then [7–9], and with a passive (spring-loaded) linear actuator in [10], and with a compact linear actuator in [11]. This paper outlines the physical implementation of the project, while the design of the novel linear actuator is presented in [12]. The structure of the designed manipulator keeps every actuator above the workspace of the manipulator. This has the benefit of helping avoid collisions between cables/actuators as well as objects in the workspace. This will make this manipulator well-suited to be positioned above a flat industrial workspace, such as a conveyor belt.

1.3. Control Platform

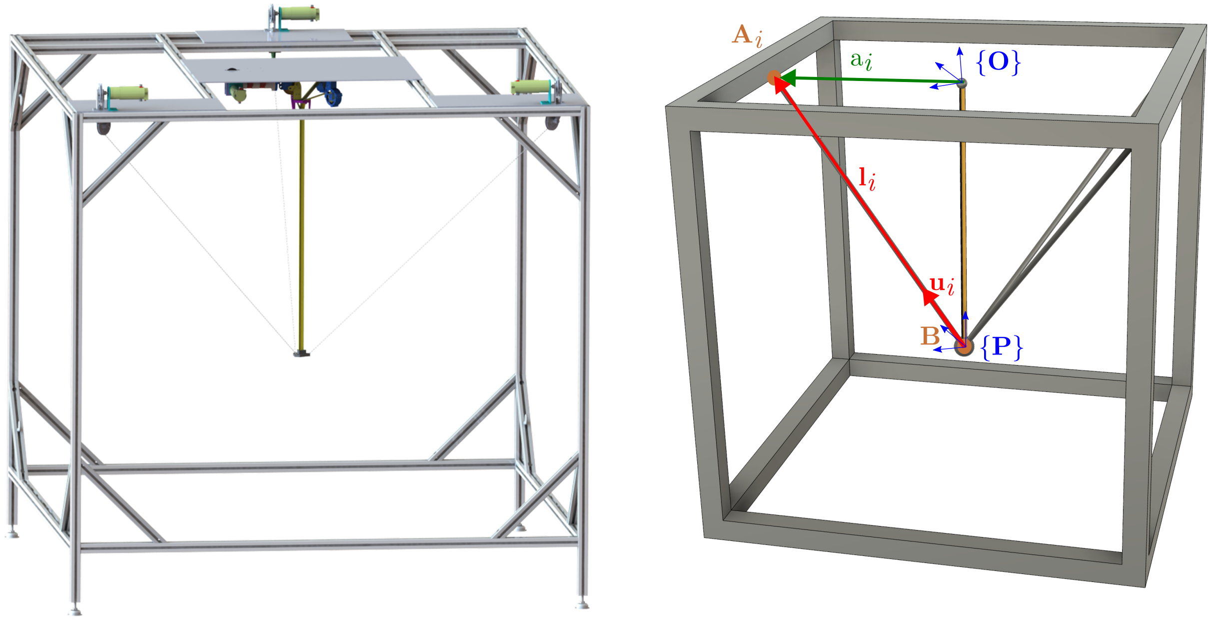
The end goal of this project is a spatial pick-and-place manipulator that can be controlled in real time as it traverses through its workspace. In order to complete this task the high-level control, which will be completed on a PC using Robot Operating System (ROS2), is a set of open-source libraries intended to facilitate the creation of robotics projects by handling the low-level communication between C++ and Python scripts [13]. The low-level control of the actuators will be completed using Arduino and DSPic microcontrollers. Sensors will be used for both position and force feedback to ensure a minimum cable tension is maintained at all times.

ROS2 is a system built for rapid, scalable, and modular development. This will help change the control systems, hardware interfaces, and communication platforms as the project develops. ROS is based on creating an interconnected system of *nodes* that communicate over *topics*. These topics can contain any number of value types such as sensor measurements, joint states, manipulator states, and control signals. Communication is allowed between nodes written in various programming languages to allow tools to more easily be built around existing software. The communication between nodes can also be configured to act as callbacks, where changes in one state can control an action in the next. A balance between speed and reliability can be decided by programmers by using quality of service settings for messages that either need to prioritize low latency or guaranteed transmission. A growing community of developers are continually creating open-source projects that can be used and built upon for future feature addition and improvements.

1.4. Kinematics

The kinematics of many CDPMs closely resemble those of the well-studied Stewart-Gough platform [3]; a 6-U$\underline{P}$S parallel manipulator that has universal (U) joints fixed to a base connected to actuated prismatic joints ($\underline{P}$), and a spherical joint connected to an end-effector (EE) or mobile platform. The simplified geometric model of cable manipulators is to be treated equivalently by assuming that each cable is a rigid prismatic link [1, 3]. A preliminary render of the actuator as well as a labelled kinematic model of the actuator are shown in Fig. 1.

While the inverse displacement of CDPMs is most often trivial, the forward displacement problem (FDP) tends to have many solutions depending on the architecture, meaning that it can not be solved in the closed form. While there are upwards of 216 solutions to the FDP of a 4-U$\underline{P}$S manipulator [14], the number of real solutions for a given architecture and set of cable lengths varies. A previous attempt at numerically solving the FDP of this manipulator with a spatial EE along a trajectory was completed in [15]. This work followed



(a) (b)

Fig. 1. Full manipulator schematic (a) Render (b) Kinematics and labels

Wampler's early work in the area [16] and made use of the Levenberg-Marquardt algorithm for non-linear and non-square problems due to the quadratic nature of CDPM FDPs.

From this prior work it was found the position alone was inadequate to fully predict the pose of a spatial EE. This led to the decision to use force sensors in the final manipulator so that a kinetostatic approach could be used instead of just using kinematics in the final control system. The other change was to shift to an approximately point-mass end-effector as four actuators are inadequate to fully control the orientation as well as the position of a spatial EE. While a point-mass attachment of every actuator is not possible in practice, the EE will have the cable and extensible linear actuator attachment points as close together as possible.

Using a point-mass approximation of the end effector causes all rotations of the EE to be uncontrollable and therefore can be ignored in the approximate model. The IDP is used to find the length of each prismatic actuator for a desired position of the end-effector, which is a matter of vector addition between the cable anchor points. That is,

$$\mathbf{l}_i = \mathbf{a}_i - \mathbf{r} \tag{1}$$

$$l_i = ||\mathbf{l}_i|| \tag{2}$$

where $\mathbf{l}_i$ is the vector from distal anchor point B to proximal anchor point A_i, which shows the line of action for each actuator i. This vector has a magnitude l_i and direction $\mathbf{u}_i$. The vector $\mathbf{r}$ is the position of the EE that corresponds to the transformation between the stationary frame $\mathbf{O}$ and the mobile frame $\mathbf{P}$. The geometry and kinematic model is shown in Fig. 1b.

The forward displacement problem is then defined as finding a desired end-effector position, $\mathbf{r}$ given a set of actuator lengths, $||\mathbf{l}_i||$. With the point-mass assumption of the end-effector, this becomes equivalent to finding the intersection of four spheres, with radii equal to the lengths $\mathbf{l}_i$ and each being centred at their respective proximal anchor points, A_i. The mathematical operation of finding the intersection of 3, 4, and sometimes more spheres fall under the name multilateration, which is commonly used in navigation systems (GPS works on the principle of trilateration).

There will be several sources of error that keep the FDP from being solved accurately in the physical manipulator. These include cable sag, imperfect cable directing, calibration errors, cable stretch, and, like in the current case, an end-effector that is not exactly a point-mass. A minimization approach may need to be used for the FDP as there is no guaranteed solution to the intersection of four spheres. Some methods for the FDP of cable robots in real-time applications use interval analysis and other mathematical tools to solve this problem based on small, finite changes to cable forces and lengths [17]. As the model becomes more realistic and fewer assumptions are made, the process of solving the FDP becomes more iterative and requires more information about the manipulator.

1.5. Statics

CDPMs, unlike standard parallel manipulators, must generally have their kinematics solved in conjunction with their statics, especially when gravity is introduced [3], or, in branch or actuation redundant cases, to determine how many (and which) cables are under tension at a given time [17]. The Jacobian matrix, $\mathbf{J}$, linearly maps the vector of actuator forces, $\mathbf{f}$, to the vector of forces experienced by the end-effector in the global frame generally referred to as the prescribed wrench, $\mathbf{w}_p$. The actuator force is a tension in the cables and tension/compression in the extensible linear actuator. For CDPMs the Jacobian matrix is simply the combination of unit vectors from the proximal cable anchor points on the frame to the distal anchor points on the EE. These vectors are found by normalizing the cable vectors such that $\mathbf{u}_i = \mathbf{l}_i / l_i$. The Jacobian matrix for a 4-U$\underline{\text{P}}$S manipulator is then:

$$\mathbf{J}^T = \begin{bmatrix} \mathbf{u}_1 & \mathbf{u}_2 & \mathbf{u}_3 & \mathbf{u}_4 \end{bmatrix} \tag{3}$$

The linear mapping between the actuator forces and the prescribed wrench of the manipulator, $\mathbf{w}_p$ then becomes:

$$\mathbf{J}^T \mathbf{f} + \mathbf{w}_p = \mathbf{0} \tag{4}$$

In this expression, the prescribed wrench is what is necessary to counteract gravity at the end-effector as well as accelerate the EE through the workspace. With a spatial manipulator this would include the forces and torques, but with a point-mass EE this is simplified to only be the resultant forces.

2. SENSORS AND ACTUATORS

The manipulator being investigated has four actuators, three of which are cable actuators and the fourth is a High Packing-Ratio Linear Actuator (HPRLA) [18]. Each actuator has its position encoded and actuator force measured. They are driven by DC gearmotors (Pittman GM14904S016-R1-SP), which have a 500 pulse per revolution (ρ) quadrature encoder and a 19.7:1 gear ratio. Attached between each actuator and the EE is a DYLY-106 S-type load cell to measure the force. These measure tension in the cable actuators and tension/compression in the linear actuator. With a mass of only 100 g each including their cables, these will cause less cable sag than most other load cells.

A general overview of the sensors, actuators, and communication systems is shown in Fig. 2. The Intel NUC (Next Unit of Computing, a small form factor PC) acts as the control PC which will be using ROS for the low-level communications, complete the path planning, control system, and kinetostatic (combined kinematics and static) calculations for the manipulator. It will send these signals to four Arduinos, one for each actuator.

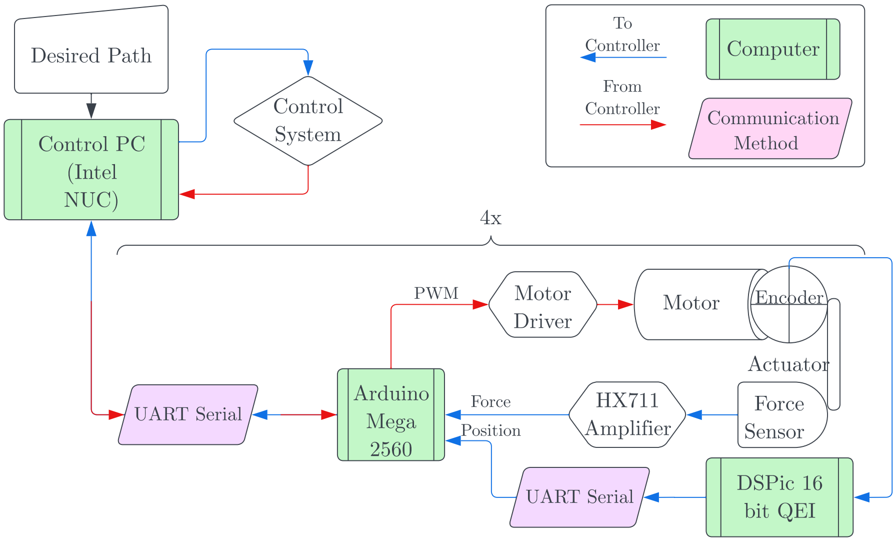


Fig. 2. Signal diagram showing actuators, sensors, and communication methods

2.1. High Packing Ratio Linear Actuator (HPRLA)

A HPRLA was developed in [18] that combines three curved leaf-springs (tape measures) into a solid rod using various attachment methods. It was found that a magnetic strip along adjacent faces with a triangular configuration made a rod that was capable of supporting over 400 N of compressive loading at a 1 m length, but under 4.5 Nm in bending. This work was continued in order to actuate these rods and create a guide that allows it to complete pointing motions similar to a universal joint [12]. The attachment to the end-effector uses a spherical joint to help avoid bending loads. A cross-sectional view of the actuator can be found in Fig. 3. This actuator has a high packing ratio in that it can be very compact when not actuated, as each of the three tapes can be compactly coiled, but it can extend to a length of over 1 m. This can be beneficial over a standard linear actuator where the stroke length of the actuator is required above the top of the workspace, so these actuators can be used in environments with limited space.

This portion of the actuator attempts to allow motions similar to a universal joint while maintaining low rotating mass and inertia. This is accomplished by actuating one of the three tapes and guiding it through a twisting and bending motion while keeping most of the material bolted to the fixed frame. The two other tapes are fed in passively to a component that guides the tapes together to form a rigid rod. The motions of the driven tapes are supported when there is only an individual tape being actuated as these are otherwise very likely to bend and buckle. A more in-depth description of the developments of this actuator is available in [12].

2.2. Cable Actuators

The cable actuators for this manipulator use beaded cables rather than the steel cable that are commonly used in comparable manipulators. These beaded cables have even spacing between the beads that have allowed for a type of "sprocket" to be developed that match their geometry. Much like a sprocket that drives a chain, these sprockets eliminate the possibility of cable slip over a driving pulley, meaning that the encoders used on the motors should be able to provide excellent accuracy for the measured lengths of each of the cable actuators. The diameter of these sprockets is approximately 9.5 cm, which was chosen based on a desired linear velocity of the cables compared to the angular velocity of the motors, as well as distributing the actuation force between several beads. During tensile testing of the beaded cable the force required to dislodge a single bead is less than the strength of the cable. Distributing the load across multiple beads

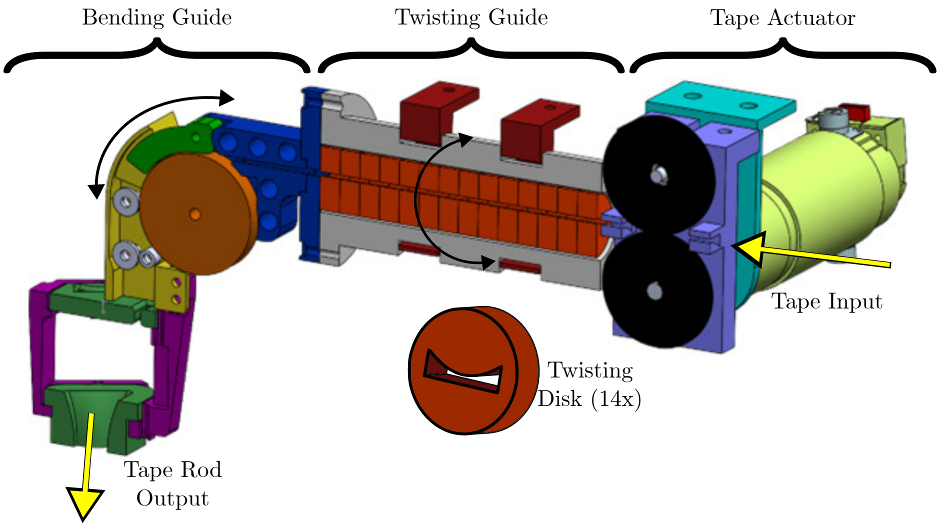


Fig. 3. Full cross-sectional view of the HPRLA. Tapes are driven by the two wheels, braced through a twisting motion, braced in bending then combined into a rigid rod.

by ensuring an adequately large sprocket diameter mitigates this problem. A cross-sectional view of this sprocket is shown in Fig. 4. Although the addition of beads increases the mass of the cables, a nylon rope with high-density polypropylene beads is used so they are still very light.

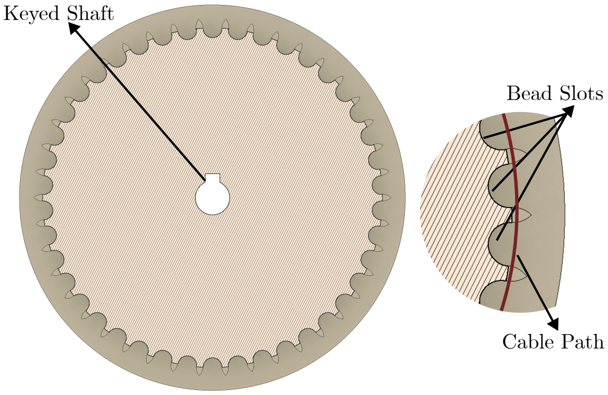


Fig. 4. Cross-sectional view of a sprocket used to actuate the beaded cable

This cable will be well-suited for low load testing and prototyping, but there are mechanical limitations that would make it unsuitable for heavy industrial applications. This cable experiences significant elastic stretching under tensile loads over a few hundred Newtons. This deformation has been found to be acceptable in the light loading conditions expected while testing the HPRLA. Future iterations of this project could use steel cable and find alternative methods to addressing slip, such as using a drum with a slot for the cable like many other researchers use.

3. SIGNAL PROCESSING

3.1. Position Measurement

Due to the high accuracy of the encoder on the input shaft of 9850 pulses per revolution (ρ) as well as the large gear ratio of the motors, this corresponds to 39400 interrupt signals on the microcontroller for each rotation of the output shaft at full (4×) resolution (ω). To ensure consistent communication between the control PC and the Arduino microcontrollers the encoder interfacing task is offloaded to a DSPic microcontroller with a quadrature encoder interface (QEI). This hardware support for encoders allows the encoder counter to be programmed in just a few lines of code to alter the registers that hold the QEI settings.

The only option for using the index pin of the encoder in the DSPic is to have it reset the count to 0 when it is activated. With nearly 20 index pulses per rotation of the output shaft, this behaviour is undesirable. To take advantage of the encoder index pin, a custom interrupt service routine (ISR) was written to correct the encoder count for any missed pulses that may have happened since the previous index. It accomplishes this task by comparing the current encoder count to the count at the previous index and ensuring that the difference is the closest gap of $\rho \times \omega$, where ω is the resolution of the encoder (1×, 2×, or 4×). This helps ensure the count is always as accurate as possible if any interrupt signals are missed from high-speed operation or having the interrupt signals from UART communication take precedence.

3.2. Force Measurement

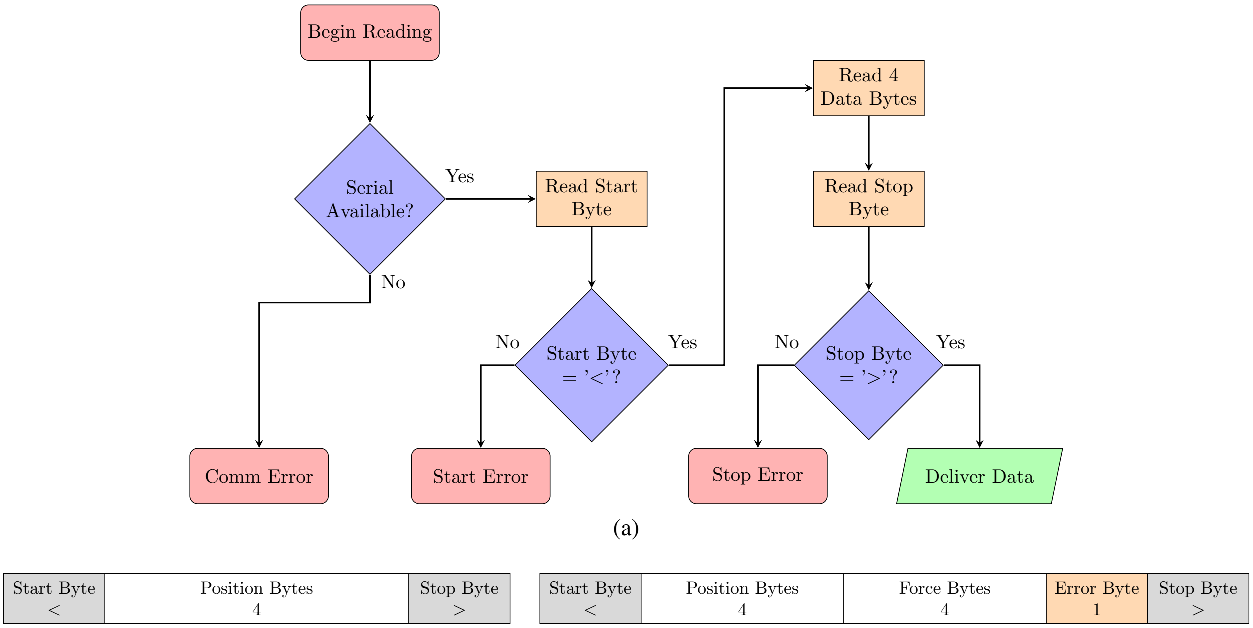
The force sensors used for this project are standard S-type load cells that function using strain gauges, which have the benefit of being suitable for both static and dynamic measurements. The signal processing for each load cell is handled by an HX711 analog-to-digital converter (ADC), which uses its own form of digital communication to a microcontroller. Interfacing this chip was completed using an open-source library [19] that allows for non-blocking communication with the processor for a more robust and real-time capable implementation.

3.3. Error Handling

Figure 5 shows the method used to improve the stability of UART communication as well as some of the data packets that are being sent between microcontrollers. To maximize the rate at which the control system can operate the communication should be as efficient as possible, so a small data packet is made to transfer bytes in a way that balances speed and stability. The addition of a byte of data in sending and receiving from the control PC to each of the Arduinos allows for an efficient way to identify problems for future debugging without manually having to monitor the communication lines at every stage.

On top of the flags used to monitor communication, error checking is also implemented to compare the position counter and force measurement from one reading to the next. While monitoring the output of the HX711 boards with readings from the load cells it was found that the signal was generally quite stable, but there were occasional erroneous readings that were completely different from all prior readings (*i.e.*, a steady +5 N reading shifting to a -200 N reading for one pulse). Although the cause of this error is currently unknown, these erroneous readings will be avoided through error checking on the difference between adjacent readings. If the erroneous readings were input into the control system, the control action could attempt to quickly fix the cable tension, possibly causing damage to the motors or system.

These simplified error messages can be used on the microcontroller side to help eliminate errors as well as in the ROS system to display errors in the command line. Using the built-in console logger commands, messages can by severity level of of *info*, *debug*, *warning*, *error*, and *fatal*. This is helpful to monitor, debug, and correct errors at every stage in the platform.



(a)

(b)

(c)

Fig. 5. UART communication details (a) Flow chart showing error checking from DSPic to Arduino (b) Position data from DSPic (c) Data from each Arduino to the control PC

4. CONCLUSION AND FUTURE RECOMMENDATIONS

This project of creating a hybrid cable-driven parallel manipulator remains ongoing but the outline of the control system and hardware implementation has been presented. The combination of ROS on the control PC for more complex calculations with Arduinos and dedicated microcontrollers to handle the signals and hardware should allow for a simple and scalable implementation. Once experimentally validated, the firmware developed for the microcontrollers as well as the overarching control PC implementation should be applicable to similar CDPMs and h-CDPMs with minimal alterations.

The next steps for this project are to finish construction of the manipulator and implement a control system. Some validation and experimentation is still required to determine how to implement path planning, forward kinematics, and a control system cohesively together for real-time implementation. In the near future of this project, quasi-static force experiments will be completed to validate prior testing on the high packing-ratio linear actuator investigated in [18]. Using a combination of the load cells on each actuator, the Jacobian matrix, and an external force sensor it will be possible to experimentally validate the capabilities of the HPRLA as well as the ability of the manipulator to properly identify its position. As the project progresses, a better model can be used to account for cable sag and stretch, differences in each actuator from ideal universal joints, and implementing proper dynamics into the setpoints of the control system.

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