2021

Designs and Practical Control Methods for Soft Parallel Robots

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Designs and Practical Control Methods for Soft Parallel Robots

Benjamin Buzzo

Thesis submitted

**to the Statler College of Engineering and Mineral Resources
at West Virginia University**

**in partial fulfillment of the requirements for the degree of
Master of Science in
Mechanical Engineering**

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Morgantown, West Virginia

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Robotic Manipulators, Agriculture, Robotic Pollinator**

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Abstract

Designs and Practical Control Methods for Soft Parallel Robots

Benjamin Buzzo

The use of soft robotics is becoming an increasingly researched topic, since they can provide more flexibility in movements and increase safety when working with humans. However, they are more susceptible to modeling and manufacturing errors in the design.

The objective of this thesis is two-fold, the first objective is to determine the benefits and limitations of using calibration tables that rely on the PWM signals instead of modeling as a control method. If calibration tables are not adequate to achieve a high level of precision. The second objective is to determine if using a tethered mobile robot in unison with a soft robotic arm is a viable control strategy and evaluating its limitations. These objectives were chosen since soft robotic manipulators are complex to control with difficult governing equations. The approaches in this thesis seek to circumvent these shortcomings.

Two different soft robots are introduced, the first being a small robotic pollination end-effector used to pollinate blackberry flowers in a greenhouse, the second is a tendon driven soft robotic manipulator. Using a calibration table on the pollination end effector yielded high precision and repeatability. However, when extended to the larger tendon driven arm it caused a large overshoot of the goal with little repeatability. The speed of the trials was slowed down and augmented by a holonomic mobile robot which eliminated the overshoot and increased repeatability.

I dedicate this thesis to my loving parents, Rachael Marie Buzzo and Randy Wayne Buzzo for all the support they've given me throughout my life.

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Chapter 1 Introduction

Robots are becoming increasingly more complex in their designs and functions, a few examples of this include utilizing soft robotic manipulators to perform minimally evasive surgeries [10] and designing robotic fish using soft actuators to achieve a natural swimming motion [11]. The use of soft robots yields numerous advantages. Examples of such advantages include un-constraining the robot's workspace to allow for infinite configurations without needing to alter the design as well as increasing safety when working in unison with humans [32]. Soft robotic manipulators can often require complex modeling to achieve accurate control [33]. The models can become unreliable when external forces are applied to the system, such as picking up an object [34]. This thesis will present two control methods: the first being the use of calibration tables to determine the forward kinematics of the robot for control on two robots. The robot designs that will be presented are 1.) a soft robotic pollination end-effector for pollinating blackberry flowers in a controlled greenhouse environment and 2.) a larger tendon driven soft robotic arm. The second control method for the tendon driven soft robotic arm the control method was later augmented with a holonomic mobile robot that attempted to mitigate the error.

For most soft robots, the physics that govern their motion can be extremely complex to understand, fully control and model the physics of in order to precisely control them. The methods presented seek to streamline control while only knowing little about the physics of the robots itself.

Chapter 1.1 Problem Statement

The objectives of this thesis are to:

1. Design and build two underactuated soft robotic systems that are controlled using the methods presented in this thesis.

2. Determine the viability and limitations of using calibration tables with motor feedback to control the underactuated systems.
3. Determine the viability and limitations of augmenting the previously described control method with a mobile robot.

It should be specifically noted that the scenarios presented in this project could be or have been reasonably completed by multiple other researchers using various methods [72] [73]. This project does not claim to solve a specific novel problem, incapable of being solved by any other method, or that it will solve the problem better than another method. Rather, this thesis aims to determine if practical methods hold any merit to be explored further.

Two scenarios were used in order to demonstrate and test this idea: The first, shown in Fig 2, is the use of a

Figure 1: The two separate configurations of the robotic arm. Without the holonomic end effector (left) and with the holonomic end effector (right).

soft robotic end-effector to precisely touch and pollinate a blackberry flower without damaging the plant itself. This

Figure 2: The robotic end effector pollinating a blackberry flower in West Virginia Universities greenhouse.

project was chosen because the natural pollinators such as

moths and bees are on a sharp decline [74]. A solution to support the increasing pollination demands is to use a robot

to do it. There are countless shapes and sizes of plants that need pollinated, so a flexible, adaptable method is desired. The drawback of this type of end effector, however, is that the physics that govern the motion can be very complex to model and a more practical method can be used to control it. The objectives of this scenario are: 1) To show a high level of control such that the end effector can be

controlled precisely as to gently pollinate a blackberry flower without damage; 2) Show a use case for this control method in a more uncontrolled environment than a laboratory setting.

The second scenario uses a one-meter tendon driven soft robotic manipulator. A Vicon system was used to generate the calibration tables that control the robot through the various experiments. The hypothesis of this scenario are: 1) To use the same calibration table idea presented in scenario 1 and extend it to a larger more complex system which is more vulnerable to errors. 2) If the robot does not achieve a high level of precision, augment the system with a holonomic robot to work in tandem with the soft robotic manipulator to achieve a desired level of precision. An example of both of these are shown in Fig 1. To my knowledge there has not been any research into using a mobile robot to help assist soft robots manipulator achieve a high level of precision.

Throughout this thesis, the assumption is made that errors caused in transporting systems between locations is negligible since the robots were re-calibrated between moves. Also, it is assumed that the feedback data that is given to the robot itself is accurate. This thesis also assumes that the feedback given to the robotic manipulator via the calibration tables are known to the robots and they can reliably assume their current positions off these tables instead of motor feedback.

The rest of this thesis will be organized as follows, first a discussion of background research on soft robotic arms and rigid robotic arms in order to provide context for the motivations behind the necessity for feedback control of soft robotic manipulators and how they compare with rigid robotic manipulators. This will be followed by background research on other soft robotic end effectors and specific agricultural robotics to show motivation for designing a robotic pollinator and thus giving a real-world application of the technique described in this thesis. This will then be followed by the mechanical design, experiment design, and results for the robotic pollination device. Next the mechanical design, experiment design, and results for the tendon driven soft robotic manipulator will be presented. Finally,

this thesis will present a discussion of the previously gathered results and then draw conclusions based on those results as well as present future works.

Chapter 2 Literature Review

For organizational purposes, the literature review has been broken into subsections as follows: Soft Manipulator Designs and Comparisons to Rigid Manipulators, Soft Manipulator Control, End-Effector Discussions, and Agricultural Robotics.

Chapter 2.1 Difference Between Discrete and Continuum Robotic Manipulators

Robotic manipulator designs can range from large industrial robotic arms for vehicle manufacturing to small soft robotic manipulators that are used for neurosurgery. An example of various types of robotic manipulators are shown in Fig 3.

Figure 3: General mechanical designs for various robotic manipulators. A non-redundant robotic manipulator (left) and a redundant manipulator (right).

The ability for a robotic manipulator to grasp and manipulate objects repeatably, reliably, and quickly has always been a very difficult challenge in the field of robotics which lead to specific manipulator designs [35]. Some robotic manipulators operate in a 3-Dimensional space and must identify

and manipulate objects in its environment, these are not trivial tasks to achieve [35]. The workspace for robotic manipulators is defined as the entire workable area that the manipulator can reach. There have been many studies that use analytical methods to find a robot's workspace [36]. For rigid manipulators, in an uncrowded workspace, they can work very effectively [37]. As more obstacles are added to the environment, the robot's workspace will be constrained making it more difficult or impossible for rigid manipulators to operate effectively [13]. There are two main classifications of rigid robotic manipulators, the first being a non-redundant, this is when the degrees of freedom that exists on the robot is exactly equal to the degrees of freedom of the desired workspace [39]. These types of manipulators yield one solution of joint states for each unique position in its workspace. Issues can arise due to having limited flexibility in regard to maneuvering in the workspace, and obstacles can significantly impact this working area. The second type of rigid manipulator is redundant manipulators, these have at least one more degree of freedom than the degrees of freedom present in the workspace [38]. These are designed such that there are multiple solutions for each end position of the manipulator. Therefore, if an obstacle is present, the robot has more possibilities to find a viable path to the desired end state. [47]

Chapter 2.2 Joint Types of Rigid Robotic Manipulators

For most rigid robotic manipulators, the modelling and control can be done through simple geometry [14]. Once the robots get more complex and more degrees of freedom are added, these control methods get more complex since multiple solutions exist for each end state [48]. Thus, optimizers have been designed and used to find optimal paths to get to a desired location [15].

When looking at the basic control of all finite manipulators, one of the easiest methods to find the desired joint locations is by using geometry [49]. Once the joint states are found the robot can use forward kinematic to reach the desired target locations [50]. There are five main types of joints that yield separate motions, all of which are shown in Fig 4, the motion of the joints are as follows [51]:

Figure 4: Five basic types of robotic manipulator joints. The Linear Joint (top left), the orthogonal joint (top right), the rotational joint (middle left), the twisting joint (middle right), and the revolving joint (bottom).

1. **Linear Joint**- The relative motion between the input and output link is translational and the axes of the two links are parallel.
2. **Orthogonal joint**- The relative motion between the input and output link is translational and the axes of the two links are perpendicular.
3. **Rotational Joint**- The relative motion between the links is rotational, where the axis of rotation is perpendicular to both links.
4. **Twisting Joint**- The relative motion between the links is rotational, where the axis of rotation is parallel to the two links.
5. **Revolving Joint**- The relative motion between the links is rotational, where the axis of rotation is parallel to the input link but perpendicular to the output link.

There is a way to determine the forward kinematics of all these joints using the Denavit-Hartenberg method [40]. The Denavit-Hartenberg method only assumes two joints rotational and prismatic (linear) however the other joints can be represented by one of these two joints. The general idea of which is that each joint is assigned a coordinate frame. Then using the Denavit-Hartenberg notation, four parameters are needed to describe how the frame (i) relates to the previous frame (i-1). The four Denavit-Hartenberg parameters are as follows [40]:

1. **a**- Is the length of the perpendicular between the joint axes which is to say the shortest common perpendicular between the two joint axis lines (Z_i) and (Z_{i-1})
2. **α** - is the amount of rotation about the X_{i-1} axis such that Z_{i-1} is pointing in the same direction as Z_i . Positive angle uses the right-hand rule
3. **d**- is the distance in the Z_i direction such that would align the X_{i-1} and X_i axes
4. **θ** - is the amount of rotation about the Z_i axis such that X_i and X_{i-1} are aligned

Figure 5: Example of a two joint robot that was used to generate table 1's mock Denavit-Hartenberg values.

These four parameters are then put into a matrix that shows the relative change between joints. For example, the Denavit- Hartenberg matrix for Fig 5 is shown in Table 1 [41].

Table 1: Mock Denavit-Hartenberg matrix from figure 3.

a	α	d	Θ
0	0	0	0
L1	-90°	D1	-90°

The transformation matrix T for each row multiplied together to get the overall robot transformation.

$$\begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i \cos\alpha_{i-1} & \cos\theta_i \cos\alpha_{i-1} & -\sin\alpha_i & -\sin\alpha_{i-1}d_i \\ \sin\theta_i \sin\alpha_i & \cos\theta_i \sin\alpha_{i-1} & \cos\alpha_{i-1} & \cos\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

For redundant manipulators there are several other ways that have been researched on how to control the manipulators in both static and dynamic environments that do not rely on Denavit-Hartenberg parameters to model their geometries [61]. There have been methods using force control by separating the motion of the manipulator into a task-space motion and inertial-space motion which allows the controller to select the dynamic characteristic in both subspaces separately [62]. Lately there has been research in the field of neural networks [63] and this has translated into the realm of robotic manipulation . Multiple studies have used neural networks to control redundant robotic manipulators and have achieved varying results, some of which were able to accurately control redundant soft robotic manipulators with high precision [64][65].

Chapter 2.3 Soft Robotic Manipulators

Soft robotics was once considered a variation on the concepts in many different sub-genres of the overall robotics field; however, it has grown so large that is now being considered a sub-genre of its own. Examples of soft robotics include a robot which used relative tracking between its soft joints connected by rigid links to achieve closed loop control [43], and a type of soft robotic actuator that uses a phenomenon known as electrostatic zipping. In general, when the dielectric material is laying uncharged and then a voltage is introduced the sides of the material begin to “zip” together [44]. Another instance of using electricity to generate soft robotic actuators was when a research group ran electric current through liquid gallium which was then used in an intelligent smart robot [45]. Generally, any type of robot that consists of some sort of soft material or soft actuator can be considered a soft robot [46].

In regard to soft robotic manipulators, there are many different ways to design them, but there are two common currently used methods. First being a tendon driven manipulator [2]. These arms work by having four or more actuated cables or tendons that pull the manipulator in desired positions by tugging on individual links attached to a central flexible column [52]. These tendon driven robots function essentially as parallel robots [53]. The robot is very scalable, and the behavior of the robot can be easily changed by re-arranging the cables [54].

The second common actuation method is to use pneumatic [55] or hydraulic [56] driven manipulators which have been used in underwater applications [57]. These arms are usually heavier, more expensive, and have more restrictions on how they can be designed. They work by adding air into a system that make up the entirety of the manipulator, depending on how much air is present in each individual bladder the manipulator bends accordingly [3][58]. For hydraulic cylinders they use incompressible fluids to achieve high levels of force but depending on speed required other components such as accumulators need to be added to the system. This significantly increases the weight and complexity of the system. Hydraulic cylinders also don't pull and push with the same forces unless running in "regen" which also requires more complex control methods in use.

For tendon driven soft robotic arms the pull of each cable is dynamic and varies widely during the transition between the two locations. Modeling the system is very difficult and computationally

Figure 6: Generalization of a 2D constant curvature approximation of a link of a soft robotic manipulator.

intensive which can lead to error being introduced into the system [4]. This has led to various methods to help minimize and validate models and predictions.

One such method is to use geometry. Using the Denavit-Hartenberg Matrix for a soft robotic arm one could take the entire length of the robotic arm and approximate it as an infinite amount of infinitesimally

small links connected by a rotary joint [42]. This would make the D-H matrix become infinitely large and thus a different method must be used to approximate the positions and use inverse kinematics. Therefore, the geometric method used is Constant Curvature where an entire length can be approximated by using intrinsic properties of the soft robotic arm and the curvature [59]. This, if modeled perfectly, can lead to highly accurate results given there are no external variables acting on the arm [60]. An elementary 2D example of this is shown in Fig 6 where k is the constant curvature of the arm and λ is the arc length.

Since this Constant Curvature model requires every parameter to be known, it can grow more inaccurate as the robot attempts to interact with heavier objects or large external forces are incorporated.

Another method for controlling the tendon driven arm is projecting the minimum and maximum torque errors in the tendon-tension space and then projecting that into the joint space of the robotic arm [16]. There are some issues with this type of control method because it requires a very accurate estimation of the dynamic parameters of the system which may not always be available. This led to a team using a neural network to perform adaptive control on these tendon driven mechanisms [17]. This does improve on the previous control methods, but it is difficult to use feedback to compensate for the error in this approach, and the control used in this project was complex even for a 2D system [17]. An attempt was made to provide a form of built in feedback control by using a mechanical stiffness controller, which put a mechanical stiffener into the arm which in turn would control the joints of said arm [18]. There is an inherent issue with this approach, that being the need to change the physical properties of the robot which if not accounted for initially could lead to the robot not behaving properly. Along the same line of thinking instead of using mechanical stiffeners, the robot is outfitted with strain gauges at key points along its body. These are then used to calculate the total curvature of the manipulator and its final position. The adding of strain gauges can significantly increase

the cost and complexity of the system depending on the desired resolution. Adding strain gauges to a system increases the cost and complexity of the system [6] [7].

Lastly a group have investigated trying to construct a highly accurate 3D state model of the tendon driven robots. The group used intrinsic arm properties as well as external forces to graph and model the system and use that for control. Without factoring in the error associated with picking up a heavy object the error of the manipulator is 6% of the length of the arm, meaning for smaller arms it would work adequately but as it is upscaled to larger arms the error becomes unreliable [19].

For the pneumatic driven manipulators, a little less research has been done but there have been groups that have investigated using Morphological computation-based control for a pneumatic arm. [20]. Another pseudo-pneumatic arm was also controlled using a Linear Quadratic Regulator to control pneumatic joints in a rigid arm. The joints act almost identically to a pneumatic soft manipulator but had issues with the joints having an error of 2cm, so it is reasonable to assume this error would increase as the pneumatic links grow in size and frequency [21].

Chapter 2.4 End Effector Designs

Robotic End Effectors come in various shapes and sizes to meet different functional performance requirements. Some end effectors are designed to be universal and accomplish many tasks but can be inept in certain scenarios, while others perform one very precise task and do it at a very high level [66]. Most of the time the designers of these end effectors do not know what objects or tasks that the robot will have to encounter thus modeling of the actual grasping motions cannot be done accurately so a universal gripper design is used more frequently [67].

A commonly used end-effector design is shown in Fig 7. This is a specific commercial end effector but the four-bar linkage used here is typically controlled by one or two motors and only seeks to open and close [68]. These types of actuators excel at picking and placing objects with handles, flipping switches and various other small simple tasks. However, plenty of innovation has been done to further increase the capabilities of robotic end effectors [69]. This has led to multiple research groups and companies attempting to make a robotic end effector that mimics the five fingers and movements of the human hand [70]. However, this type of design can require complex control algorithms and contain a large number of motors to control precisely.

Figure 7: A general mechanical design of a rigid robotic manipulator that is similar to the design of many commercial robot manipulators.

Given the complexity of using a human-like and other high degree of freedom manipulator approach some newer research has been invested into soft robotic end effectors which has led to a vast number of designs. Some of these end effectors are easy to control, consisting of only one actuator to drive them. There have been attempts at using tactile sensors to get force feedback when gripping

objects [8] or using a reduced order finite element model with a state observer [9].

There has also been some research done into the world of parallel robotics which are a mechanical system that uses several computers controlled serial chains to support a single platform, or end-effector [25]. One of the most famous parallel robots is called a Stewart Platform shown in Fig 8 [26]. These manipulators have been

Figure 8: Stewart Platform that uses six actuators to control a single rigid plate [71].

widely used in flight simulators to simulate the motion of the aircraft.

If rigid serial manipulators are designed poorly there can be a high amount of unwanted sloppiness and flexibility which can be amplified the longer each individual link grows. With a parallel robot since one platform is supported by multiple linkages, this sloppiness can be canceled by the other linkages and the same rigidity can be achieved at smaller lengths leading to high precision and high speeds of motion. The downside to parallel robots is the limited workspace for the number of degrees of freedom that the robot has. A parallel robot can achieve a similar workspace as a serial robot but requires more actuators on average [25].

Chapter 2.5 Agricultural Robots

The agriculture industry needs keep up with the growing world population. This industry can benefit from robots that automate processes which are increasing in demand. There have been several groups developing different robots to help in this industry.

First, there have been numerous studies that investigated the effectiveness of automated robots picking and handling fruits. There was a robotic end effector developed in 2013 that used four fingers, with foam padding, controlled by a solenoid that would wrap around tomatoes and bring it towards the center of the end effector. The center was a suction tip that would grab onto the tomatoes and then twist at such an angle that it would pick the fruit. This worked well with a 95.3% success rate [27]. More research has been done looking into apple picking using robotic grippers, one such group developed a low-cost gripper that used pressure to suck the apples in and then used blades to cut it from the tree. However, the focus here was to design a gripper that was low cost which led to control issues [28].

The picking of fruits isn't the only instance of robots assisting this industry, since natural pollinators are on the decline there has been a push to increasingly use artificial pollination methods. One such example is that of an Unmanned Aerial Vehicle that would fly over a tomato field and, using its

downwash, it would create a sizeable force that would mimic a gust of wind and pollinate flowers [29]. The issue with this approach was that not all plants are ready to accept pollination at a given time, meaning, multiple complete runs every day had to be performed to hit the pollination windows of every fruit. Another such example was that of a robot that was equipped with an air assisted sprayer that could target and spray individual flowers, with a successful pollination rate of 79.5%. [30]. Since pollen is becoming increasingly more expensive and scarce this method must depend on gathering and transporting live pollen before it becomes unviable and distributing it to acceptable plants. A novel example of a robot that actively collects the pollen from live flowers and attempted to distribute it is one from 2017 [31]. The robot was a small Unmanned Aerial Vehicle that used hair mimicking bee fur. It was designed as a proof of concept that something like a remote pollinator could exist. An issue with this was that due to size and battery life it may require hundreds of these individual UAV's to successfully pollinate a field of plants in each pollination window [31]. West Virginia University has made a robot that works inside a greenhouse to pollinate bramble flowers which is highlighted in the following section [12].

Chapter 3 Precise Pollination End-Effector

The following chapter will present and discuss the mechanical design, experimental design, control methods, and results for the precision pollination end-effector. The precision pollination end-effector was field tested in a large greenhouse on site at West Virginia University [12]. Results on repeatability and uncertainty of the overall flexible plate are stated as well as the results from flower pollination.

Chapter 3.1 Mechanical Design

The robotic pollinator went through many different iterations and variants. This was done because of the unique design requirements and challenges that arose from testing these multiple variations. These requirements are listed below.

1. The pollinator shall pollinate individual flowers that are viable for pollination while ignoring unviable flowers.
2. There shall only be a three to four-day window when each flower is viable for pollinating.
3. Each flower has a 2cm in diameter.
4. The end effector shall grab the pollen from the stamen and transfer it to the pistol in order to pollinate the flower.
5. The end effector shall have the capability to reach odd angles to pollinate all flowers.
6. The end effector shall be able to pollinate the flower without damaging it.

Initial concepts considered did not physically touch the plant, examples include using air or sound to remotely disperse the pollen from the stamen in hopes that it would land on the pistol. However, these concepts were soon disregarded since blackberries on the same cluster are not viable for pollination at the same time, thus a more precise pollination method was desired, and the precise physical pollinator concept was explored.

The first of the physical pollinators designed was a claw shown in Fig 9. The claw had flexible fingers that allowed for a cotton tipped rod to be inserted into it. Cotton tipped rods were

Figure 9: The Claw design .

Figure 10: Single Actuator Flexible Plate design.

Figure 11: Tri-Plate Flexible Plate design.

chosen because of the tiny tips of cotton that can grab and distribute pollen easily. All fingers were controlled by a singular linear actuator placed in the center that allowed the manipulator to transition between an open to closed state. The general idea was in the “open” state the gripper would collect the pollen from the male part of the flower and then as it transitioned to its “closed” state it would be able to distribute that pollen to the female portion of the flower.

The next design attempted to keep the simplicity of control by using the same two states, “open” and “closed”, but in order to shrink the working area, a flexible plate was considered shown in Fig 10. The actuator was connected directly to the ring (shown in yellow) that would fold the flexible plate from the “open” position to the “closed” position.

Another flexible plate was looked at which added two more actuators to the design making a total of three. Each actuator was connected to a 120-degree section of the ring (in orange) shown in Fig 11. This allowed for increased freedom in the workspace and the plate could flex to more desired locations with the independent actuators.

All previously described designs used 50mm stroke linear actuators. A design was considered where the actuators size was increased to have a stroke length of 140mm, this was then angled inward by a cone. The three actuators were attached directly to a flexible plate, this was controlled as if it was an underactuated flexible parallel robot (Fig 12). The cone was added to help guide the actuators in the desired direction.

The final design that was compared removed the cone in favor of a ring and the actuators were reduced in size. Which allowed for the overall size of the design to be reduced significantly (Fig 13).

Figure 12: Long Flexible Parallel Robot design.

Figure 13: Short Flexible Parallel Robot design.

The trade study that was used is shown in table 2 the values ranged from 1-5 where 1 was the worst performer in the category and 5 was the best performer in that category. The totals were then summed together, and the design with the highest number got selected.

In the trade study table Manufacturability is the ease of fabricating the individual components of the end-effector. Most parts were 3D printed and some parts required more advanced printing methods and strategies which took longer and had a

higher failure rate. Control is the ease of how the end-effector could be controlled and the amount of motors required to fully control the device. Size is the volume of the device, where the smaller was more advantageous. Workspace is the range that the end-effector could operate from a fixed position, the wider and larger the workspace generally the more advantageous. Pollen collection is the ability to collect and transfer pollen reliably and effectively. Construction was how difficult the device was to put together once all the parts of were manufactured, the easier to assemble was more desirable.

Table 2: Trade study that compared all of the pollinator designs together, the values ranged from 1-5 with 1 being the worst and 5 being the best.

	Manufacturability	Control	Size	Workspace	Pollen Collection	Construction	Total
Claw Pollinator	3	5	1	2	1	2	14
Single actuator Flexible Plate	5	4	5	1	1	2	18
Tri-Plate Flexible Plate	4	3	2	3	2	3	17
long flexible parallel robot	2	2	3	4	5	1	17
short flexible parallel robot	1	1	4	5	5	5	21

As can be seen from Table 2, the Claw Pollinator was the easiest to control along with the single actuator flexible plate. However, it was large and did not collect pollen efficiently due to the cotton tipped rods being smaller than the larger plates used in other designs.

The single actuator flexible plate manipulator was easy to manufacture and control and was very small, all things that were advantageous, however it lacked a large and flexible workspace and did not collect or transfer pollen well due to the cotton tipped rods. This design also consisted of many parts making it difficult to put together.

The Tri-Plate and long flexible parallel robots both were average in most categories. The Tri-Plate flexible robot only outperformed the rest of the designs in manufacturability. The long flexible parallel robot had the same pollen collection capability as the short flexible parallel robot since both designs used the same flexible tip.

Lastly the short flexible parallel robot was hard to manufacture and control. This was due to the difficulty in modeling the flexible tip and the use of three linear servos. Advantages of this design were

Figure 14: The workspace of the robotic pollinator, completely retracted (left), extended fully (middle), largest angle achievable (right).

it was small in size with a large flexible workspace and used few parts making it easy to construct while also transferring pollen effectively, this design is shown in Fig 14. Using the decision matrix shown in Table 2 the short flexible parallel robot was chosen for experimental trials. The end effector tip was chosen to be made of soft cotton and later replaced by goose feathers as to not damage the flower.

Chapter 3.2 Experimental Design

The flexible tip of the parallel robot was difficult to model accurately due to limited resources for modeling flexible materials. To circumvent this a calibration table was generated. The calibration table mapped the motor locations to the end states of the flexible plate. The motor locations were obtained by logging the PWM signals that were sent to them at a given time. The plate orientation was obtained by attaching an Aruco marker to the end plate shown in Fig-

Figure 15: Calibration process for finding the flexible plates approximated orientation using an Aruco marker.

15. The calibration table was then made by correlating the PWM signal to the orientation of the plate at each time interval. Even though the end effector would bend a little the end effector was still able to reliably output its position from the Aruco marker.

Once the calibration table was generated it was then used to create a pollination routine. It was determined that the best way to distribute the pollen from the stamen to the pistil was to fold the stamens gently into the pistil of the flower. Once this pollination routine was decided the Aruco marker states and corner positions were recorded. The robot also pollinated eight flowers these flowers were then compared to self-pollinated plants and hand pollinated plants.

Chapter 3.3 Results

The results are presented in two sections, the first being the results to show the repeatability and control of the pollinator. The second is to show the effectiveness of the pollinator.

Chapter 3.3.1 Repeatability and Control Results

To judge the level of repeatability that this control method yielded, the device was put through 20 cycles of the pollination routine. The end effectors states [x y, z, roll, pitch, yaw] were recorded. Since the plate could flex and bend which could alter the results of the Aruco marker, therefore the individual corners of the Aruco markers were recorded. The 20 cycles were performed together with no rest in between cycles. The results are shown in Fig 16 -Fig 17. Test runs where the tip of end effector was manually measured and compared with the Aruco output were ran to validate the results.

Figure 16: The general path of the robotic pollinator as it performed its pollination routine. Top left, top right, and bottom left are the center of the end effectors X, Y, and Z position respectively. In the bottom right graph, it depicts the four corners of the Aruco marker tracker. Purple is the top left corner, yellow is the top right corner, blue is the bottom left corner, and orange is the bottom right corner.

Figure 17: The robotic pollinator's orientation as it progressed through the pollination routine. Top is the Roll of the plate, middle is the pitch of the plate, and the bottom is the yaw of the plate.

Fig 16 show the pose of the center of the flexible plate. As can be seen the center of the plate did not move significantly in the XY plane, however when looking at Fig 16 the corners of the plate move significantly in the XY Plane. This is due to the plate folding during the pollination routine. Each corner of the Aruco marker tracked is represented by a different color in Fig 16, and the corners all follow a similar pattern. When looking into the repeatability of the control method within each graph the individual cycles do follow similar patterns and trends however the overall errors are small. This could be due to the overall translation and movements being small, the total Z motion being 5mm. When looking into the overall rotation of the pollination routine while the end effector oscillates drastically, the cycles do follow general trends but with the travel being so minimal it is still difficult to determine the effectiveness of the control method when extrapolated to large displacements. For smaller travels as shown in this experiment, we can get an adequate level of repeatability.

Chapter 3.3.2 Pollination Effectiveness

To test this control method in a more uncontrolled environment an experiment was conducted to test the pollination effectiveness of the device. In a greenhouse, the robot used the same pollination sub routine described previously to pollinate eight blackberry flowers. For comparison another eight flowers were hand pollinated and eight flowers were self-pollinated. After a period of time the berry size, shape, and the number of drupelets were

Figure 18: Evaluation of pollination methods. Representative images of blackberries (from left to right) pollinated by spontaneous selfing, by the robot, and by hand using a paint brush (A). The number of drupelets (B) and size of berry (C) varies depending on pollination method. Bars represent the mean $\pm$ SE ($n = 10$). The same letters indicate no statistical difference among pollination methods. [75].

recorded. An example of the resulting berry from each pollination method is shown in Fig 18 from left to right the control [75], robot pollinated, and hand pollinated. As can be seen from the top graph when comparing the columns there were slightly more drupelets pollinated using the robot over the control however it was not statistically different and there was significantly less drupelets pollinated than hand pollination. However, the berry size was statistically larger using the robot pollination opposed to the control, but the hand pollination still yielded significantly larger berries overall. Note that the end effector here was handheld and not controlled by the larger autonomous robot. This could have led to different results than if the robot itself was using the end effector, however these results can be used as a proof of concept.

Chapter 4 Tendon Driven Soft Robotic Arm

This chapter will present and discuss the mechanical design, experimental design, and results for the tendon driven soft robotic arm. The arm was tested in a small-scale environment capable of accurate tracking using a Vicon motion capture system.

Chapter 4.1 Mechanical Design

The overall objective of this scenario was to design a soft robotic manipulator and control it using a calibration table accurately. The arm was designed to fit these following requirements:

1. The arm shall be able to flex rather easily and not resist motors too much.
2. The arm shall be larger than 30cm but smaller than 100cm.
3. The arm shall be able to be tracked using the inhouse Vicon system.
4. The arm shall be able to carry a 50-gram object.
5. The arm shall be controlled using only off the shelf servos.
6. All parts shall be easily made or bought off the shelf without advanced machining capability.

A couple reasons exist for the requirements chosen above. The first being the arm was to be made as simple as possible to allow for other researchers to be able to reproduce the results effectively. The height requirement was to allow for the robot to be manageable yet long enough that given the opportunity significant error could build up in the system. The tracking via the Vicon system was desired to yield accurate end position locations for data collection and calibration table generation. The object size and weights were chosen because they would be about the size of a golf ball which is something that everyone can reliably compare results to.

A tendon driven soft robotic manipulator was chosen since it would be the simplest to design, build and control. A 1-meter arm was chosen because it was small enough to be manageable in an

indoor environment but large enough that it could accumulate large amounts of error. The guiding vertebrate were made from 3D printed PLA using an Ultimaker 3, which can print parts up to 0.2mm resolution and the fabrication time for all arm components were under six hours. The separation between vertebrate (the white 3D printed disks) had to be large enough that the Vicon tracking markers would not be occluded. The motors chosen were 140mm stroke length linear servos that had up to 200N of thrust. These servos were chosen since they have been used widely in the Interactive Robotics Laboratory and have internal feedback control that allows for precise motor movements built into the system.

There is a total of five 7.5cm diameter vertebrate used spaced 14cm

apart, which was done to allow the robot to bend freely without risking the vertebrate hitting one another preventing flexibility. The vertebrate is attached to the 6mm Low Density Polyurethane spine by two shaft collars that are clamped to each vertebrate insuring no unwanted motion. The robot is controlled by a 6-channel Pololu servo controller that is capable of sending independent Pulse Width Modulation (PWM) signals to each of the four servos. A picture of the robot is shown in Fig 19.

Figure 19: Mechanical design of the soft robotic arm.

Chapter 4.1.2 Robotic End-Effector Design and Control

After a couple experiments were performed using only the calibration table, it was hypothesized that attaching a holonomic robot to the overall system could increase the performance. This is what lead to the final objectives listed above. A picture of the assembly with the robot attached to it can be seen in the right half of Fig 1. There were many reasons behind this. Firstly there has been a lot of research done in the ability to track and control mobile robots. If one could leverage this research and apply it directly to a soft robotic system. The Interactive Robotics Laboratory has used different methods

to accurately track and control mobile robots in the past and this knowledge could be transferred to this application with ease. As of this thesis, there has been no attempt to use soft robotic manipulators to drive a robotic end effector to its goal location, this would blaze new ground. Lastly this could further extend cooperative robotics by using two conjoined robots together, leveraging their individual strengths, to achieve a common goal.

This type of combined system could be used in an obstacle rich environment in which a robot is tasked to go between waypoints that are separated geographically. This system would allow the robotic arm to move the robot between the geographically separated locations and then as the robot traverses said environment the obstacles would not restrict further motion due to the flexibility of the arm.

When designing the robot a few requirements were considered:

1. The robot shall be able to easily move in any direction on the horizontal plane.
2. The robot shall always be normal to the ground in all orientations.
3. The robot shall be relatively small to fit the size of the arm.

The robot attached to the end effector was chosen to be holonomic so that it can drive in every direction; this would allow for easier control. The robot was attached to the arm using a 3D printed 2-piece ball joint so that the robot would always be normal to the ground. The robot is also just big enough to house three hobby grade continuous rotation servos and three omni-directional wheels. The motors are powered via computer USB that is routed through the same pololu controller that controls the arms motors, so no on-board power is needed.

Figure 20: Top down view of the holonomic robot (left), and the vector addition method used to generate the resulting motion of the robot (right).

The robot is designed so that all three wheels run through the very center of the robot. This is done so that the robot can use vector addition to control the direction the robot travels. A diagram of the robot and how the vector addition works is shown in Fig 20. The idea is as follows;

1. Use the Vicon system to detect the difference between the robotic end-effector and the goal location.
2. Find the resulting vector that would get the robot from its current location to its goal location.
3. Use vector addition on the three wheels to drive the robot to the goal location.

Chapter 4.2 Experimental Design

Before the experiments could begin, a calibration table had to be generated. This was done using a Vicon system to track the end position of the robotic arm and the motor positions.

The objectives of the following experiments were to:

1. Determine if using a calibration table could accurately control a soft robotic system with multiple solutions.
2. Determine if the speed at which the robot moved could affect the overall accuracy and performance of the system.
3. Determine the merit and limitations to using a mobile robot in cooperation with the robotic arm.

The first experiment that the robotic arm underwent was to alternate continuously between two waypoints, a “Rest” waypoint and a “Target” waypoint as fast as the robot could. This experiment was performed to see the merit of using the calibration table on a larger soft robot and to understand the limitations of such a method.

The second experiment performed was to once again move the robot between a “Rest” waypoint and a “Target” waypoint, however this time the robot had a period of time where once the robot determined it had reached the desired destination it would pause for a brief duration before continuing to the next waypoint. This was done to see if giving the robotic arm an opportunity to rest between waypoints could increase the performance without further complication to the system or the controller.

The last experiment performed used the same robotic arm as previous experiments however, a holonomic robot is attached to the end of the robotic arm. The robotic arm and the holonomic robot together would move to a “Target” waypoint. This was performed to see if any merit exists in using a mobile robot attached to a soft robotic arm, if it could increase the overall performance of the system, and to understand the limitations of doing so.

Chapter 4.3 Results

The results for the robotic arm are broken up into two separate categories, the first being when the robotic arm was controlled solely by the calibration table, and the second being when the robotic end-effector was attached. In the graphs there is reference to a “Target” position and a “Rest” position. These positions are the two waypoints that the robot moved between in each cycle and their values are $[-42, 7.6, -553.2]$ mm and $[0,0,0]$ mm respectively. The target location was chosen at random.

Figure 21: The path of the robotic arm shown in blue compared to the predicted path shown in orange. Top is when the robot is moving between the waypoints as fast as possible and bottom is when the robot has a brief duration to pause between runs.

Figure 6: The X Y and Z position of the robotic arm when moving between the target and rest waypoints. The black line is recorded path that the robot took. The yellow line is the "rest" position boundary, and the orange line is the "Target" Position boundary. The robot is moving between the waypoints as fast as it can.

Figure 23: The X Y and Z position of the robotic arm when moving between the target and rest waypoints. The black line is recorded path that the robot took. The yellow line is the "rest" position boundary, and the orange line is the "Target" Position boundary. The robot is moving between the waypoints with a brief pause once it reaches the waypoints.

The following tables took the data gathered from the experiments showed in Fig 21 - Fig 23 and calculated the mean, standard deviation, and maximum error. The "Rest" waypoint and "Target" waypoint were separated to investigate if there are significant changes between the two waypoints

Table 3: The calculated mean, standard deviation, and maximum error for the X, Y, and Z position of the robotic arm as it traversed the waypoints as fast possible.

	X Rest Position Error	Y Rest Position Error	Z Rest Position Error	X Target Position Error	Y Target Position Error	Z Target Position Error
Mean [mm]	5.76	-0.80	-3.99	-7.15	10.21	-21.09
Standard Deviation [mm]	1.88	0.31	2.38	0.83	0.82	4.69
Max Value [mm]	8.37	1.5	6.28	10.1	11.22	29.2

Table 4: The calculated mean, standard deviation, and maximum error for the X, Y, and Z position of the robotic arm as it traversed the waypoints with a brief pause at each waypoint.

	X Rest Position Error	Y Rest Position Error	Z Rest Position Error	X Target Position Error	Y Target Position Error	Z Target Position Error
Mean [mm]	4.57	-1.81	0.53	-7.96	8.71	-26.81
Standard Deviation [mm]	0.67	0.25	2.08	0.40	0.39	3.08
Max Value [mm]	9.72	-3.12	13.64	10.3	10.1	33.2

Fig 21 illustrates the predicted path shown in orange, and contrasts that with the actual robot path shown in blue. This was done in order to provide a visual representation of how the robot behaved during these experiments. The first series of graphs show the state of the robotic end effector as it moved between the two waypoints. As can be seen, the more cycles that it performed the larger the error grew. This is due to the robot swinging after hitting each waypoint. When looking at Table 3 mean error for all three position at both the “Rest” and the “Target” waypoint were between 0.8mm to 21.09mm with the standard deviation also ranging between 0.31mm to 4.6996mm. The large disparity between the numbers is possibly due to the Z position having a significantly larger travel distance than the Y position. When comparing these results to that of Table 4 while the overall mean error between the waypoints is similar ranging from 1.8111mm to 26.8mm the standard deviation of the number significantly decreased ranging from 0.2537mm to 3.088mm. This shows that while the overshoot error was still present in the system the overall range of values became more accurate.

Chapter 4.3.3 Soft Robotic Arm with Holonomic End Effector Results

The following results were conducted using the tendon driven soft robotic arm in cooperation with the holonomic mobile robot end effector. The robotic arm initially attempted to move towards the target waypoint. After the robotic arm finished moving, the holonomic robot then found the difference between its current position and the goal position and generated a velocity vector towards the goal position, as the robot was driving the robotic arm also would make minor adjustments to move towards

the goal location. Unlike the previous trials the robotic arm did not complete these cycles continuously; instead, each trial was run after the robotic arm was manually reset to its starting state.

Figure 24: The path the robotic assembly traveled between rest and the target location shown in black compared with the straight-line path between the rest and target position shown in orange.

Figure 25: The path that the assembly took to reach the target location. The path the robot took shown in black and the target location shown in orange. Top shows the X position, bottom shows the Y position.

Table 5: The X and Y position errors and standard deviation of the assembly when traversing to the target location. Note that Z position was not looked at since the robot necessarily had to always remain on the ground.

	X position error	Y position error
Mean (in mm)	-0.75	2.15
Standard Deviation (in mm)	1.90	7.78

Since the robotic arm and the holonomic robot worked together in this experiment Fig 24 illustrates a straight-line path (shown in orange) between the rest position to the target waypoint and contrasts that with the actual path (Shown in black) the robotic system took. It is seen that the path would tend to arc in both directions and not follow a straight-line path. Once the assembly overshoot the target waypoint it would severely arc towards the goal location. When looking at the Fig 24 the assembly would briefly overshoot the target waypoint but eventually settle closer to the goal location. Table 5 shows the X and Y mean errors being very small 0.759mm and 2.15mm respectively. The standard deviation being 1.90mm and 7.78mm respectively shows that while the precision of this approach improved over previous trials the accuracy stayed close to or worse than previous experiments.

Chapter 5 Conclusions and Lessons Learned

The data gathered from the experiments show a few interesting details. The robotic pollinator used in this thesis was able to be controlled well enough such that it could successfully pollinate flowers. Due to the small travel distance of the robotic pollinator it was difficult to determine the effectiveness of the control method used but the overall path between the trials trended in the same direction. When used in the greenhouse to pollinate flowers the robotic end effector could reasonably fold the stamens into the pistols and cause pollination. The end effector controller also allowed it to be gentle enough that when performing the pollination routine, it would not severely damage the flowers. Overall, when looking at the data from Fig 16 and Fig 17 it can be concluded that the small robotic end effector could be controlled competently enough to achieve its desired tasks.

When this control method was extended to the larger more complex robotic arm, it greatly underperformed. The robotic arm would yield a mean error in the Z direction of up to 21.1mm when moving fast and did not improve when moving slow yielding a mean error 26.81mm. However, the standard deviation did improve between the fast and slow trials this led to the idea that possibly attaching a holonomic robot to the end of the robotic arm could take the results seen from the slow trials and improve the mean error by using the mobile robot to correct said errors. The robot did correct the errors reducing the maximum mean error seen to 2.15mm however the standard deviations drastically deteriorated, therefore this experiment yielded a tradeoff between precision and accuracy.

When attaching the holonomic robot to the robotic arm an unexpected result occurred. The overall workspace of the robotic arm, in this case a bowl shape, changed. The holonomic robot could only traverse from the center of the original workspace outward and at the edges of the workspace it was unrestricted, this changed the workspace from a bowl shape to a torus shape. The robot used in the experiments was a lightweight 3D printed robot with relatively weak motors compared to that of the

robotic arm. This caused the robotic arms tension and motors to greatly affect the holonomic robot and changed its driving patterns from straight to arced which can be seen in Fig 23. The tension of the robotic arm would tilt the robot up at times which occasionally caused one wheel to be off the ground and result in the robot going to an unexpected location. Since the original workspace of the robotic arm was a bowl shape the holonomic robot would tend to get stuck when it was in the center of the workspace, once the robot started to drive however, it would free itself and proceed without issue to the target location. All of this being said the robot assembly was still able to traverse repeatedly to a set target location precisely. Overall, this thesis provides one of the first proof of concepts where instead of a robotic arm being mounted on a mobile robot, the mobile robot is mounted onto the robotic arm. This thesis has shown that while there are limitations to this approach, there is merit into further research in this topic.

Chapter 6 Future Works

The use of a holonomic robot as an end effector in this thesis was a proof-of-concept experiment. Future works should expand on this topic by putting a similar system in an environment with obstacles and geographically separated locations. This could demonstrate the benefits of using both types of robots together to achieve a goal that neither robot could do independently. Also, future work should include a cooperative planning algorithm that creates more seamless motion between the two systems. Another future expansion on this topic would be to outfit the mobile robot end effector with a gripping mechanism that would allow it to transfer object from one location to another. Also, this could be expanded by using a more complex robot as an end effector with more instrumentation and stronger motors or modifying the wheeled style robots with that of a legged style robot. This could mitigate the problems stated in this thesis where the robot would get stuck or be pulled by the robotic arm. An even further expansion on this concept would be to outright replace the mobile robot end effector with a Unmanned Aerial Vehicle, this would, instead of decreasing the workspace of the overall assembly, it could increase the workspace allowing the robotic arm to reach areas it normally could not while also removing the restriction of the end effector needing to be touching the ground allowing for more overall freedom and flexibility in the system.

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