PERFORMING OVERHEAD TASKS WITH SUPERNUMERARY ROBOTIC LIMBS

by

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ABSTRACT

Overhead tasks such as those frequently found in aircraft manufacturing pose health risks to the workers due to the strain imposed on the shoulders. To reduce the risk of injury, a set of supernumerary robotic limbs (SRL) were designed to perform these overhead tasks. The SRL is designed with limits in the hardware and software to protect the human and prevent collisions between robot and operator. The arms are designed to have a workspace above and in front of the head of the user free from singular configurations so the robot is free to operate where the tasks will be performed. To further protect the human, the mount that attaches the SRL to the shoulders was redesigned to be lighter and to better distribute the load. In this manner, the shoulders will become less fatigued from the static load of carrying the SRL. To complete the task of positioning cables and routing them through the ceiling of an airplane, a winch end effector was designed to latch onto the fuselage arches and pull the cable through these arches. In order to control the SRL, the concept of principal components analysis was used to reduce the input space. This concept was specifically used to map the motion of the operator’s hands onto the appropriate speed for the winch motor to operate. In this manner, the winch would pull the cable at the same rate that the human fed the cable. The human would then be able to control the speed of the winch simply by executing the task at whatever pace they so desired.

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I cannot thank my parents enough for all of their help and support over the years. Whenever I needed anything I knew they were always just a phone call away. Although I couldn’t implement all the lasers my dad was hoping for, I still greatly appreciated the advice that he and mom always had to offer.

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Chapter 1

Introduction

1.1 Motivation for and Difficulties with Implementing Robotics in Aircraft Manufacturing

In the aircraft industry, the average age of workers has been increasing. As this trend continues, Boeing has been looking for ways to protect these aging workers. Like most manufacturers, they are also always looking for ways to constantly improve their efficiency and manufacturing techniques. Due to these influences, the Boeing Corporation has tasked us to design a robot to aid the workers in their many duties.

In 1913 when Henry Ford introduced the first assembly line to one of his automobile plants, he kicked off a movement that revolutionized the automobile industry. These assembly lines made the production of cars much more efficient, and allowed for a relatively simple implementation of automated robots to the assembly process. The assembly line brings the parts to the stationary robots, where the robots can perform their simple task over and over. Unfortunately, this assembly line technique is not effective in the aircraft industry, and so the automation of this manufacturing process has also proved more difficult to implement.

Due to the size and relatively low output of aircraft, an assembly line is simply not feasible. So while the product comes to the workers or robots in the case of automobiles, with aircraft the workers and possible robots must come to the plane. Due to the difficulties of scaling the scaffolds used in aircraft construction and other navigational difficulties, creating a fully automated robot to perform necessary tasks inside the plane is unfeasible. The answer is to
supplement the navigational capabilities of the human with the untiring precision of a robot by creating a wearable robotic solution.

1.2 Concept behind the Supernumerary Robotic Limbs (SRL)

Prior products have already been designed to combine the best of man and machine. The field of prosthetics has been making great strides recently. Prosthetics replace lost limbs with robotic substitutes. These products have shown the ability for humans to adapt to robotic extensions of their bodies and to fully interact with them.

![Figure 1.1: A man successfully uses a prosthetic device to complete everyday tasks.][1]

Prosthetics would not be useful for our goals, as they are merely designed to replace lost limbs, and we seek to augment the capabilities of humans. Rather than replace limbs, we will add more limbs.

Another common method of combining man and machine is found in exoskeletons. These exoskeletons typically increase the load carrying capabilities of a limb or set of limbs. They give the user the unfatiguing strength of a machine, while still relying on the superior sensing and mobility of the human.
However, these exoskeletons still have their limitations. By attaching themselves to the limbs of the human, they do not serve to extend the workspace of the human, but instead simply work to increase the human's performance within that workspace. Additionally, the human arm must go wherever the robot goes. For overhead tasks such as what Boeing seeks to accomplish, the human arms would still need to be up in the air to complete the task even with the aid of an exoskeleton, so they would still feel the strain from lack of proper blood flow to these extremities.

These limitations of previous combinations of man and machine have led to the idea of creating supernumerary robotic limbs (SRL). The concept of the SRL is to add independent robotic limbs to the human that can aid the human in completing tasks.

1.3 Potential Uses for the SRL

The limbs of the SRL can offer many advantages to the human. These limbs can be designed to work outside of the workspace normally accessible to the human. Additionally, they can safely work in the areas of the workspace that can be harmful to humans after prolonged periods of labor, such as the overhead region. With proper use of the SRL, the workplace shoulder injuries related to such tasks could be drastically decreased. The SRL can also work on symbiotic tasks
with the human, such as holding a panel in place while the human fastens it. This serves to cut the necessary manpower for such tasks in half.

1.4 Thesis Layout

This thesis will focus on the specific task of routing cables through the ceiling of an aircraft. The task involves lifting the cables up to the ceiling, pulling the cables through specific holes in the roof arches, routing the cable through succeeding arches, and finally firmly attaching the cable in place. To accomplish this task, the workspace of the robot needs to encompass the ceiling area to properly feed the cable, while at the same time the workspace needs to exclude the region around the operator's head for safety reasons. The robot will need to be able to successfully pull the cable from the floor and route it through the proper course in the roof. Per request of Boeing, the robot will not use voice commands, but will instead rely on the gestures of the operator to control it.

The following are the chapters of this thesis.

1. Chapter 1 introduces the concept of the SRL and its potential uses.
2. Chapter 2 describes the kinematic model for the system, and specifically describes the workspace.
3. Chapter 3 touches on the improvements made to the mount structure.
4. Chapter 4 describes the end effectors necessary to complete the tasks.
5. Chapter 5 introduces the concept of primary components and how it is implemented to control the robot.
6. Chapter 6 discusses the results of the work done and suggests future work.
Chapter 2

Kinematic Model of the System

2.1 Constraints for the Kinematic Model

When creating any robot that works with humans, safety is a very important issue. Safety is all the more critical when the robot will be worn by the human as in this case. In order to fully ensure the safety of the operator, the movement of the robot must be constrained in two ways. The position of the robotic limbs must be limited from entering the space of the human with both limits in the code controlling the movement and mechanical constraints that do not allow the robot to contact the human. In this way, even if there is a malfunction with the software, the hardware is physically limited from harming the human.

The next most important factor to consider is the workspace of the robot. The end effectors need to have full access to the area that they will be working on in order to perform the necessary tasks. While approaching singular configurations may be desirous for some tasks that robots perform such as supporting loads, the task we will be focusing on is quite different. For the task of routing the cables, the winch and cable routing arms need to have the freedom to reposition themselves in all directions to adjust to wherever the cable may be and to reroute where the cable should go. If there was a singular configuration in the middle of this workspace, the robot might not be able to move as necessary to correct the movement of the cable. Thus, for this task it is important that the robot is able to reach the desired workspace and not be in danger of entering into any singular positions.

The degrees of freedom for the arms determine the variety of configurations they can take. To be able to reach any point in the desired three dimensional workspace located above the head of the operator, the arms need at least three degrees of freedom. However, the orientations of the arms...
are often also important, so more degrees of freedom may be necessary. The kinematic model was then designed keeping in mind the factors of safety, workspace, and degrees of freedom.

2.2 Kinematic Model

The basic structure of the arms can be seen in Figure 2.1. The arms each consist of two links with two motors at both joints, giving four degrees of freedom to each arm. The arms are symmetrical in both their links and their motor configurations. The arms are mounted just above the shoulders of the user to a mount that is fixed to the body of the operator. The mount is discussed in further detail in Chapter 3.

Figure 2.1: Kinematic diagram for the arms of the SRL.

The arms were designed to mimic the structure of human arms in order for the operator to become more comfortable with the movement of the arms. Thus θ₁ and θ₂ rotate about the x axis, similar to the motion that a human shoulder makes to swing the arms during walking. These motors allow the arms to rotate over the head of the human and into the desired workspace. The motors that control θ₃ and θ₄ are directly attached to the first set of motors, and allow the arms to bend outwards as needed. They are mechanically constrained to not come inwards towards the human head; that is, θ₃ and θ₄ have a range of -90° to 90°. Links 1 and 2 were designed to be
long enough to extend over the head of the operator, with each measuring 13.5 in. Because of this, $\theta_7$ and $\theta_8$ were also allowed to have a range of motion from $-90^\circ$ to $90^\circ$, and were mechanically constrained from motion outside of this range. In this manner, the first link of each arm was long enough that even when the joints were fully bent inwards, the forearm would be safely above the head of the user.

In order to operate the robot and send the endpoints of the arms to the proper coordinates, the kinematic equations must be found relating the joint angles to the endpoint coordinates. Because the arms are symmetric, we will simply develop the equations for one arm, as the second set of equations is then trivial to find. To find the equations for the right arm, I will use two coordinate systems. The first coordinate system is relative to the mount, and the second is relative to the endpoint of link 2. The positioning of the second coordinate system is shown in Figure 2.2.

![Figure 2.2: The second coordinate system is shown fixed to the endpoint of link 2.](image)

The $x$, $y$, and $z$ coordinates of the endpoint of link 2 can be easily found in the first coordinate system. From Figure 2.1, the following relations are derived:

\[
x = l_2 \cos \theta_4 \\
y = l_2 \sin \theta_4 \cos \theta_2 \\
z = l_2 \sin \theta_4 \sin \theta_2
\] (2.1)
Similarly, it is simple to find the coordinates of the endpoint of link 4 relative to the endpoint of link 2 using the second coordinate system. Looking at Figure 2.2, the following relations are derived:

\[
x_1 = l_4 \cos \theta_8 \\
y_1 = l_4 \sin \theta_8 \cos \theta_6 \\
z_1 = l_4 \sin \theta_8 \sin \theta_6
\]  

(2.2)

In order to comprehensibly describe the endpoint coordinates of link 4 relative to the mount in terms of the first coordinate system, the relationships from Equation 2.2 must be converted into the first coordinate system and then added to the relationships in Equation 2.1. To accomplish this, the relation between coordinate systems 1 and 2 must be found. The relation between coordinate systems can be described as follows:

\[
\begin{bmatrix}
    x \\
y \\
z
\end{bmatrix}
= 
\begin{bmatrix}
    \cos \theta_4 & -\sin \theta_4 & 0 \\
    \sin \theta_4 \cos \theta_2 & \cos \theta_4 \cos \theta_2 & -\sin \theta_2 \\
    \sin \theta_4 \sin \theta_2 & \sin \theta_4 \cos \theta_2 & \cos \theta_2
\end{bmatrix}
\begin{bmatrix}
    x_1 \\
y_1 \\
z_1
\end{bmatrix}
\]  

(2.3)

The matrix from Equation 2.3 can then be used to transform the coordinates in Equation 2.2 into the first coordinate system, which will give the coordinates of the endpoint of link 4 relative to the endpoint of link 2 in the first coordinate system. By combining Equation 2.2 with Equation 2.3, the following result is achieved:

\[
\begin{bmatrix}
    x \\
y \\
z
\end{bmatrix}
= l_4
\begin{bmatrix}
    \cos \theta_4 \cos \theta_8 - \sin \theta_4 \cos \theta_6 \sin \theta_8 \\
    \sin \theta_4 \cos \theta_2 \cos \theta_8 + \cos \theta_4 \cos \theta_2 \cos \theta_6 \sin \theta_8 - \sin \theta_2 \sin \theta_6 \sin \theta_8 \\
    \sin \theta_4 \sin \theta_2 \cos \theta_8 + \sin \theta_4 \cos \theta_2 \cos \theta_6 \sin \theta_8 + \cos \theta_2 \sin \theta_6 \sin \theta_8
\end{bmatrix}
\]  

(2.4)

Finally, to relate the endpoint coordinates of link 4 to the mount in terms of the first coordinate system, the matrix from Equation 2.4 must be added to the relations in Equation 2.1. Combining these two equations leads to the final solution as follows:
\[
\begin{bmatrix}
\cos \theta_4 \\
\sin \theta_4 \cos \theta_2 \\
\sin \theta_4 \sin \theta_2
\end{bmatrix}
+ \frac{1}{\sqrt{2}} \begin{bmatrix}
\cos \theta_4 \cos \theta_8 - \sin \theta_4 \cos \theta_6 \sin \theta_8 \\
\sin \theta_4 \cos \theta_2 \cos \theta_8 + \cos \theta_4 \cos \theta_6 \sin \theta_8 - \sin \theta_2 \sin \theta_6 \sin \theta_8 \\
\sin \theta_4 \sin \theta_2 \cos \theta_8 + \sin \theta_4 \cos \theta_6 \sin \theta_8 + \cos \theta_2 \sin \theta_6 \sin \theta_8
\end{bmatrix}
\] (2.5)

By using Equation 2.5, we can now directly compute the endpoint coordinates of the arms in a coordinate system fixed to the mount of the SRL given the angles of each joint.

Because the endpoint coordinates are relative to the mount of the SRL, it is apparent that it is important to properly fix the mount to the human. Unnecessary and unwanted movement of the mount, such as slipping on the shoulders or moving up and down when the arms are raised and lowered, will cause more disturbances for the robot to account for. It is important that the mount is firmly attached to the human, while also allowing the human to operate through a full range of motion without being hindered by the mount. The design of the mount to accomplish these goals is further described in Chapter 3.
Chapter 3

Mount design

3.1 Previous Mount Design

In previous years, an initial prototype for the structure of the robotic arms and how they attach to the human had already been developed. The design was fully capable of proving the initial concepts behind the project, such as teaching the robot to successfully interact with the human by recognizing the movements and intentions of the human and taking actions accordingly. An isometric view of this original prototype is shown in Figure 3.1.

![Isometric view of the original mount prototype.](image)

However, there was still much to be done. The design carried excess weight, and did not distribute the weight properly on the human. It is especially important to avoid excess weight, as fatigue from static loads such as wearing the SRL design takes longer to recover from than fatigue from dynamic tasks, as the lack of movement impedes blood flow which in turn makes it harder for the body to remove the waste products of the exertion. In a study of male letter carriers by Wells et al. (1983), it was found that the prevalence of shoulder pain for the letter carriers was 13%. When the load carried by these postmen was increased by approximately 38%,
the prevalence of shoulder pain jumped to 23% [3]. From this study, it is clear that an excess static load to the shoulders must be avoided for the safety and well-being of the users.

An additional shortcoming of the first prototype is the distribution of the weight of the robot to the human. The SRL puts all of the weight on the top of the shoulders of the user, which puts a lot of pressure in those small areas. This pressure soon leads to discomfort for the wearer.

The initial prototype places the arms of the robot well above the shoulders of the human. While it is necessary to mount the arms above the human shoulders to allow for full mobility of the human arms, placing the robotic mount too high simply increases the lever arm of the reaction forces acting on the robotic shoulder mounts about the axis of the human shoulders. This leads to excess torque on the human, which should be avoided.

Finally, the ingress and egress of the initial prototype was found to be difficult and time consuming. In my design of a new prototype shoulder mount, I looked to solve these problems to create a comfortable and more enjoyable experience for the user. This comfort is not simply for the morale of the workers that may use it in the future, but for their safety as well.

3.2 Inspiration for the Mount Design

When attempting to create a new radically altered design for the shoulder mount, I began by researching existing technologies for bearing loads upon the shoulders. One of the first items I discovered were shoulder mounts for large video cameras. An example of one such camera mount is displayed in Figure 3.2.
These camera mounts are effective at comfortably distributing the weight of the camera on the shoulder of the user. Unfortunately, these mounts are typically designed to be supported by a single shoulder, and also must be held up by the handles at the front of the mount. The SRL on the other hand will need to be supported on both shoulders, and will need to stay in place through a wide range of body positions without the support of hands keeping it steady.

Despite these drawbacks, there are still some useful lessons to be learned from the camera mounts. In order to comfortably place the load on the shoulder, the mount has a curved shoulder rest that attempts to follow the general contour of the shoulder. Instead of simply resting on the very top of the shoulder like a flat surface would, this curved mount spreads the load across the front, top, and back of the shoulder. Additionally, the camera mounts uses firm foam padding inside these shoulder rests. This padding allows the shoulder rest to further conform to the exact shape of the current user of the mount. This padding serves to further reduce any pressure points caused by the mount. However, because control of the camera position is very important, the foam is kept firm so the mount stays in place on the shoulder. This will also be important with the SRL, as it will need to stay in place on the shoulders of the wearer in order for the SRL to compute its position accurately.
I was next inspired by football shoulder pads. Shoulder pads are attached to the shoulders and upper chest area, but still allow for a wide range of arm motion. They stay firmly attached to the body, and distribute loads well. All of these features are important for the mount design. A set of football shoulder pads is displayed in Figure 3.3.

![Football Shoulder Pads](image)

**Figure 3.3:** Football shoulder pads allow for a wide range of motion. [5]

The range of motion is very important, as the user of the SRL should be comfortable and unhindered from performing their tasks, most of which will occur above their head. As previously mentioned, firmly mounting the SRL to the body is important for the SRL to be able to position the end effectors appropriately. Finally, the loads must be distributed well to protect the user from injury.

In order to allow almost full range of motion for the arms, the pads that cover the shoulders are flexibly attached to the chest pads. This way, when the arms come up the shoulder pads rise up with them. For the SRL, it was desired that the shoulder mount point would remain in place, while still allowing for freedom of movement. So unfortunately it was apparent that the robotic arms could not simply be mounted to something similar to these shoulder pads. However, the arms could instead be mounted to the inner shoulder, similar to the location the shoulder pads are attached to the rest of the pads. This inner shoulder area stays fixed in place, while still allowing the outer shoulder to move freely.
In order to fit more snugly and distribute loads more effectively, shoulder pads extend down across the chest and the upper back. The former SRL prototype was prone to rotate about the axis extending from shoulder to shoulder, so extending the mount across the chest and back would be an effective method to combat this rotation. By mimicking the design behind football pads, the rotation could be stopped while still allowing for the arms to move unimpeded in front of and behind the torso.

The final important feature of the football pads is that although they fully enclose the upper chest and shoulders, they are still simple enough to put on and take off. Even though the initial prototype for the mount was mostly on top of the shoulders, it was still difficult to take on and off. The football pads simplify this process by opening up the front and allowing the two sides of the pads to hinge around the back. In this manner, the pads can more fully encompass the human while allowing for ease of ingress and egress.

The concepts behind the camera shoulder mount and the football shoulder pads were the most important pieces of inspiration for the SRL shoulder mount design. The camera shoulder mount stressed the importance of the mount following the curve of the shoulder, while the football pads demonstrated how to firmly attach a structure to the shoulder and upper torso without restricting movement. These features were then implemented into the design of a new set of shoulder mounts for the SRL.

3.3 Initial Design Prototyping

In order for the mount to fit comfortably and snugly, it was important that the inner shape of the mount matched the contours of the human. Additionally, the mount would need to properly fit a range of people, and not simply follow the exact curves of a single person. In order to
accomplish this, I decided to first fit the curves as closely as I could to my own body to establish a starting point. With those curves in mind, I would then offset the curves and make up the difference with padding. Similar to the padding found in camera shoulder mounts, this padding would serve to better fit a wide range of shoulders. Additionally, different thicknesses of padding could be used to accommodate persons of significantly differing sizes.

The first step to accomplishing this was to find a set of curves that would properly fit my shoulders, back, and chest. To create these curves, I used calipers to measure out various points across my shoulders, back, and chest in the area that the mount would be. Due to the size of the proposed mount design, I knew I would want to divide the mount into separate pieces for the chest, shoulders, and back. This would allow for parts small enough to be created in the 3D printer. Additionally, if there were any minor changes to be made in the future, only the effected parts would need to be reprinted, rather than wasting material remaking the entire mount. Since I planned on separating the mount into shoulder, back, and chest pieces, I then fitted three distinct curves to the points I had measured to represent these distinct parts.

Although the full prototype would be created with a 3D printer, I did not want to waste the material while I was merely trying to fit the curves properly. So, in order to fit the curves I instead used the laser cutter to create the cross sections for the parts I planned to make. Using this method, I could rapidly prototype a variety of curves until I found the set of curves that would best fit. Even though I knew specific points for the curve to go through, it was still important to test out a variety of curves going through these points. If the curves were too concave, the mount would only touch the body at the specific points that were measured, which would result in uncomfortable pressure points. If the curves were too concave, the mount would not be able to fit all the way down on the shoulders, and the mount would be unstable.
Besides the addition of the chest and larger back pieces, I also wanted to attach the mount to a vest to fully secure the mount to the body. A vest would be flexible enough through the abdomen that it would not interfere with the movement of the human. However, a vest would not be able to rotate about the axis running from shoulder to shoulder of the human. This is in contrast to the previous design, which relied on straps running under the arms to hold the mount to the person. The vest was chosen for its mesh construction which would allow for the mount to attach virtually anywhere on the vest, and for the pockets that could be used to hold extra end effectors and tools. These end effectors will be more thoroughly discussed in Chapter 4.

3.4 Full Mount Prototype

With the cross section curves properly fitted, a three dimensional prototype could now be constructed. The first new mount prototype consisted of six pieces. It contained two chest pieces, two shoulder pieces, and two back pieces. The two back pieces were connected by a hinge to allow for ease of ingress and egress, and the chest pieces could be held in place with a latch. The latch had a safety lever to prevent the latch from opening unexpectedly, in order to ensure the mount stayed properly fixed to the human while in use. A front view rendering of the Mark II mount prototype is shown in Figure 3.4.

![Figure 3.4: Front view of the Mark II mount prototype.](image-url)
Coming down from the shoulders, the chest pieces curve in to the middle, similar to how the football pads are cut to give the arms and chest room to move. In the bottom corners and along the middle of the chest pieces are holes, similar to what can also be found along the shoulder and back pieces. These holes serve as permanent attachment points to the vest worn underneath the mount. The chest pieces also feature large grooves running most of the way from top to bottom on the inside of the mount. These grooves serve two important purposes. First, the grooves cut away excess material, making the mount lighter for the human. Second, the grooves also allow for additional ventilation, which helps keep the user cool and comfortable.

Figure 3.4 also shows how the shoulder pieces only rest on the inside of the shoulders. Although the mount rests on the inside of the shoulders, the mount needs to extend over the shoulders so the robotic arms can hang outside of the arms of the human, allowing for unimpeded movement for both the human and robotic arms. In order to reach this point, the shoulder pieces extend to the mounting location for the arms at an upward slant that takes them out of the way of the human shoulders beneath.

As previously mentioned, the shoulder pieces are considerably more fitted to the curve of the shoulders than the shape of their predecessors. This contour allows the weight of the mount to be distributed across the shoulder from front to back, rather than simply resting all of the weight on the highest point of the shoulders. The two designs can be seen in Figure 3.5.

![Figure 3.5: Side view comparison of the curve of the shoulder area.](image)
Figure 3.5 also shows that the height of the mounting location for the robotic arms above the shoulders was reduced. As previously stated, this reduction in height above the shoulders was important for minimizing the torque felt by the shoulders when the human bends forward. Previously, the mounting location was 1.3in above the shoulders, but in the Mark II prototype it was reduced to .5721in above the shoulders.

The back plate was changed from a rigidly connected piece in the prior prototype to a pair of back plates connected by a hinge in the Mark II prototype. This allows the mount to open up when the user is putting it on or taking it off, but coupled with the front latch it keeps the two halves of the mount firmly connected when in use. The back plate and hinge design are shown in Figure 3.6.

![Back view of the Mark II prototype.](image)

The cut of the back plates allow for them to be out of the way of the shoulder blades while still extending down the back. The large holes at the top of the back plates are for wiring purposes. These holes allow the wires to pass from the robotic arms through the mount itself back to the back plate to connect to the motor controllers. This keeps the wires safely stowed and protected from the moving robotic arms.
Even though the Mark II prototype features the addition of the chest pieces and has back pieces that extend farther down, the Mark II still manages to be significantly lighter than its predecessor. While the original mode weighed 1843g, the Mark II weighs a mere 1074g, or 58% of the original weight. This was accomplished by cutting away excess material wherever possible. This drastic drop in weight coupled with the increased contact surface area between the human and the mount makes the mount much more safe and comfortable for the human to wear.
Chapter 4

End Effectors

4.1 Winch End Effector

For the task of routing the cables, the robot needs to be able to pull the cables from the ground or off of a roll up into the ceiling of the aircraft. It needs to be able to handle irregularities in the cables, such as occasional zip ties used to hold cable bundles together, and preferably it should be able to handle a variety of cable sizes so that the end effectors are not limited to narrow ranges of cables, leading to a large number of necessary end effectors. The end effector should be light enough that the robot can easily move it into position, and so that the balance of the operator is not disturbed while the robot is performing this movement. The end effector should be able to mount to points in the roof structure to steady the robot during the task, and ideally should allow some freedom of mobility to the operator while the end effector is braced to this structure.

With these requirements in mind, the design for the winch end effector was developed. A rendering of the winch end effector is shown below in Figure 4.1.

![Figure 4.1: Isometric view of the winch end effector.](image)

The end effector uses two rollers to pull the cables. One roller is directly actuated by a motor, and the other roller is free spinning. The free spinning roller is mounted on a set of tracks that
allow it to travel towards and away from the drive roller. This degree of freedom allows the winch to adjust for small local changes in cable thickness such as the occasional zip tie wrapped around the cables passing through, as well as adjust for major differences such as differently sized bundles of cables. An extension spring is mounted to the housing of the free spinning roller to pull it towards the drive roller. This spring supplies the clamping force that allows the winch to pull the cables without the cables simply slipping back out. As the cable size increases, the clamping force also increases. This is important to offset the additional weight that comes from larger cables.

The hooks on the front of the winch allow the end effector to attach to the structure of the aircraft during the task. By attaching to the structure of the aircraft, the winch is able to send the gravitational force on the cables into the airplane instead of down onto the human. It can also be made possible for the SRL to pull itself up by these hooks to lessen the load of the robot on the human during this task. By this attachment, the reaction force from pulling the cable is also sent into the aircraft structure. In this manner, the SRL does not need to expend energy to maintain a fixed position while constantly exerting a force to pull the cable through.

The winch end effector also provides an additional degree of freedom in the attachment to the arm of the SRL. This spring loaded bearing in the arm allows the operator to turn in place while the winch is rigidly attached to the aircraft in order to look backward at where the cable is going to ensure there are no blockages in the way. The bearing is spring loaded so that when then winch comes up from the rest position into the workspace, the winch will always be in the same position so the worker knows where to expect it. This also speeds up aligning and attaching the winch to the aircraft structure, as it will already be facing the correct direction. The back of the winch and the adapter to connect to the arm are shown in Figure 4.2.
4.2 Guiding End Effector

The second end effector necessary for the task of routing the cables is an end effector to guide the cables. The end effector needs to be able to keep the cable from falling onto the human after it comes through the winch, and guide it backwards to the next opening for the cable to pass through in the roof structure of the airplane. The end effector also needs to be able to know where to go and adapt to changes in the posture of the SRL operator. Finally, the end effector need to be able to release the cable when the operator is done routing that cable and is ready to move on.

The resulting end effector design is shown below in Figure 4.3. After threading the cable through the loop when it first comes through the winch, the end effector is then able to steer the cable to its target. The camera shown installed within the end effector is a Ximea xiQ camera capable of reaching frame rates of 500fps. This camera allows the use of computer vision to ensure that the cable is routed to the correct position. This way, even if there are differences in where the holes are relative to each other that the cable must pass through, the SRL will be able to account for the discrepancy and still correctly route the cable.
The gap in the loop is to allow the end effector to disengage from the cable when the operator is done with the cable and ready to move on. The cable is able to slip through the gap, but the gap is placed in a position where the cable will not accidentally slip through during the task.
Chapter 5

Control of the Robot

5.1 Motivation for Gesture Control

In order for the robot to perform any tasks, an operating system must be put into place in order for the user to control the motion of the robot. Many applications such as toys rely on remote controls to operate. For this purpose, a remote control cannot be used as the operator will need to use their hands to complete the tasks and cannot have them constrained to pressing buttons. Most manufacturing robots tend to be fully autonomous and repeatedly follow the same trajectories. This works well for assembly lines where the piece that the robot needs to work on is always delivered to the same spot in the same state, so that the robot rarely needs to adapt to any abnormalities. However, in this case the robot is not stationary but mounted on a human. The human may approach each task in slightly different ways, and the surroundings may change from one assignment to the next. Thus, the robot will not simply be able to follow a fixed trajectory, but will need to respond to changes in conditions and what the operator wants. Finally, voice commands can also not be used, as the robot will be used in potentially loud environments where such commands could either go unnoticed or other sounds may be mistaken for cues.

The solution to these constraints is to use gesture control, where the robot reacts based on the movements of the human. In this manner, the human can operate the robot simply by performing their half of the task, and the robot recognizes what it should do and acts accordingly. The robot can also respond to differences in the movements of the human, and thus adapt to any abnormalities in the environment. With this method agreed upon to be the proper direction, it is now necessary to determine how the robot is to interpret the gestures of the operator.
5.2 Principal Component Analysis

In order to control the winch speed through the gestures of the operator, we will be starting with an input space of 1800 data points from the IMUs for each time step. How the specific number of 1800 was arrived at is further explained in Section 5.3. Unfortunately, trying to use all 1800 data points to compute the optimal speed for the winch motor at every time step is unfeasible, so the input space must be reduced. By using the partial least squares regression (PLSR) technique, the principle components can be determined to drastically reduce the input space. PLSR is a widely used technique to solve a wide range of problems that require input reduction [6, 7, 8].

For an input space of size m, the first step is to plot all of the data points x in the m dimensional space. We then project the vector to each of these points onto the unit vector v. From this we get the equation for z, the length of the projection of each vector x extending to each point onto the vector v. This equation is given simply by the following:

\[ z = x^T v \]  

(5.1)

This process is shown in Figure 5.1.

Figure 5.1: The vector to point \( x_i \) is shown projected onto vector \( v \) to produce the scalar variable \( z_i \). [9]
Vector \( v \) is then placed in the direction that gives \( z \) the highest correlation to the output \( y \). In the testing, the motors are back driven so that the algorithm will know the optimal value for the output \( y \). Once this has been accomplished, the original 1800 variables have been reduced to a single variable \( z \) that describes the output \( y \). The value for \( z \) is multiplied by a coefficient \( c^0 \) to produce the predicted output value \( \hat{y} \). The value for \( c^0 \) is determined by minimizing the mean squared error between the ideal output \( y \) and the predicted output of \( \hat{y} \). However, this single variable may not completely describe the output \( y \). In this situation, more principal components are obtained to produce a stronger correlation between the principal components and the output \( y \). To achieve this, the process is repeated. This time though, instead of finding the ideal correlation between \( z' \) and \( y \), \( z' \) is instead correlated to \( y - \hat{y} \). In this manner, the second principal component is the component which most effectively explains the variation in \( y \) left unexplained by the first principal component. As more principal components are added, the correlation grows stronger, but more data must be processed.

5.3 Controlling the Winch Speed

The operation of the winch pulling up the cable is a prime example of where gesture control is necessary. While the winch is pulling the cable, the operator will have their hands full feeding the cable at an appropriate speed and making sure it does not get kinked or wrapped around anything on its way up. While they are busy doing this, they are unable to dedicate their hands to simply pressing buttons to control the feed rate. Instead, the feed rate will be based off of how quickly the operator cycles their arms up and down to feed the cables.

In order to create this control system, the first step was to perform multiple tests of manually feeding the cable through the winch while moving the hands up and down in the same manner as
during the real task. For the first run, the operator made as many extraneous movements as possible, while the winch was unused throughout. In this manner, the algorithm could learn what movements to disregard when calculating winch speed. After the initial test, nine more tests were run under more typical conditions. That is, as the operator fed the cable, the cable was pulled through by an assistant in order to back drive the motor. During these tests, the speed that the cable was being fed through the winch was varied. In this manner, the algorithm could learn to relate different hand feeding speeds to winch speeds.

During these tests, the computer took data samples every millisecond of the speed that the winch was being back driven, as well as six different measurements from three IMUs located on the operator. The operator wore an IMU on each wrist and a third attached to the back of the shoulder mount. The six measurements given by the IMUs consisted of accelerometer and gyroscope data for the x, y, and z directions. A sample data set is shown in Figure 5.2.

![Figure 5.2: Sample data from winch speed test. Top graph displays winch speed, bottom graph shows IMU readings.](image)

Rather than use negative values, the motor signifies counterclockwise motion with values from 0 to 999 and clockwise velocities with values from 1000 to 2000. This can be seen in the motor speed graph during the first second of the test. The motor was pushed slightly clockwise three times while the winch was being placed into position, as evidenced by the three spikes. Once the
pulling actually began approximately two seconds into the test, the IMU data can be seen to be quite regular from the steady motion of the hands moving up and down to feed the cable.

A total of ten tests (including the first test to teach the algorithm which movements to disregard) were performed. Seven of these tests were then used to find a correlation between the movement of the operator's hands and the winch speed. The first step in synthesizing the data from these tests together was to normalize the data. Figure 5.3 shows the data before and after normalization. The graphs on the left show the normalized data, while the graphs on the right represent the preprocessed data. The top graphs are taken from the IMU data, and the bottom graphs are from the motor speed data.

![Figure 5.3: Preprocessed and normalized data from the IMUs and winch motor. Clockwise from top left: Normalized IMU data, preprocessed IMU data, preprocessed motor speed graph, normalized motor speed chart.](image.png)

After the data was normalized, a regression was then found in order to map the IMU data onto the motor speed data. The input space did not simply contain the 18 values from the IMUs at that particular moment, but also the values over the past second. This means that the total input space was of size 18000. For efficiency, only one in every ten data sets was kept, to downsample the space to 1800. The eigenvectors necessary for the transformation were computed, and ranked in order of largest eigenvalues. The larger eigenvalues correspond to a greater impact of the specific IMU measurement on the output winch motor speed. By using this method, the IMU
measurements with the strongest correlation to the motor speed can be found, allowing for the rest to be disregarded. This allows the input space to be severely reduced, which in turn increases the processing speed of the controller. Rather than using all 1800 data points, only the most important IMU data at the most important times are used.

The weight of each eigenvector was found by dividing the corresponding eigenvalue by the total sum of eigenvalues. It could then be seen how much of the variance in the output speed could be explained by the correlation derived between the IMU data and the motor speed for a given number of principal components used. The chart in the upper left of Figure 5.4 shows that over 50% of the variance can be described with just three principal components and almost 70% can be described with the ten most important principal components.

Two of the three tests that were not used to find the correlation between the IMU data and the motor speed were used to validate the correlation. The correlation was used to predict what the motor speed should be given the IMU input data, and then compared to the actual motor speed data taken from the test. In the bottom left graph of Figure 5.4, the predicted data is shown in green superimposed on the actual motor speed data in blue. It is clear that the predicted data very closely resembles the actual motor speed data. The predicted motor speed can be seen rising in the beginning, plateauing at a very similar speed to the actual speed, and then trailing off at the end. The motor speed is also notably always in the correct orientation.
Figure 5.4: Results of principal component correlation. Clockwise from top left: Chart displaying total variance described by the number of principal components used, prediction of what the motor speed should be based off of the IMU input data, actual motor speed during the test, predicted and actual motor speeds overlaid on top of each other.

In order to better display the relation between the sensor data and the predicted motor speed, Figure 5.5 shows the input data being received by the controller. As seen in the figure, the IMU data shows a clear increase in activity when the motor begins to turn. This cyclic movement is repeated until immediately before both the predicted and actual motor speed are shown to slow down.

Figure 5.5: Concurrent data from predicted motor speed, actual motor speed, and sensor input respectively.
Although the testing produced a reasonably strong correlation, previous similar testing for arm movements had produced stronger results. This may be due in part to the difficulty of back driving the winch motor at the correct speed relative to the arm movement. If the cable was not pulled through quick enough to make the motor match the speed of the arm movement, the cable would get backed up in front of the winch and the actual speed measurements of the motor would not reflect the optimal speed. For the experiments involving the arm movements, it was much easier to make the robotic arms follow the motion of the person, as the movements were larger and the lever arm with which to back drive the motors was also greater. Additionally, the testing to relate the hand motion to the winch speed differed significantly from previous testing in that it involved a cyclic process of moving the hands up and down to the same positions, rather than the previous experiments which involved constantly moving the arms to altogether new positions.
Chapter 6

Conclusion

In this work, a solution to alleviate the stresses that come from working on tasks above the head was sought in the field of robotics. The answer found here was found in the form of the SRL, which can perform the tasks so the human does not need to work with their hands constantly above their heads. Not only does the SRL make the workplace safer for the human, but it is also capable of reducing the number of workers necessary to complete a task.

The improved mounting structure for the SRL serves to further improve the conditions for the operator. Studies have shown that constantly bearing a static load can lead to shoulder injuries, so it was important to both reduce the weight of the robot and increase the area that the weight of the SRL is spread out over across the chest, shoulders, and back. The mount is also attached more firmly, so that the robot is better at following the movements of the human, and there are fewer unexpected movements of the mount from slipping that the arms would need to account for.

The task of positioning and pulling the cables would of course not be possible without the end effectors. The winch end effector is able to attach itself to the structure of the aircraft, in order to transfer the load of the cables onto the plane instead of the human. Additionally, this allows the structure of the plane to take up the reaction force of pulling the cable, so the SRL does not need to expend large amount of energy to steady the winch during the process. The design of the winch also ensures reliability over a wide range of cable sizes with the spring loaded design.

Finally, in order to drive the winch at the proper speed, it was shown that the motion of the human hands could be used to change the winch speed, such that the winch would pull the cable at the same rate that the cable was fed to it by the operator. Such a system would allow for an
intuitive and hands free way for the operator to control the SRL while performing the task. The robot would simply follow the same pace set by the operator, so that the operator does not feel rushed or hindered by the robot.

Future work should be focused on enhancing the robustness of the design. Certain elements such as the wrist joint in the winch end effector are weak and prone to failure. Additionally, the comfort of the shoulder mount could still be improved. Modeling the weight distribution across the mount could be used to create a more ergonomic design. An important factor to consider is that the standby position places all of the weight of the SRL behind the operator, so the mount must be able to support this without rotating backwards around the shoulders.

The initial experiments with the SRL provide a glimpse of a promising future for the concept. The SRL is currently capable of completing a variety of tasks, such as supporting ceiling panels and positioning a winch to pull cables up through the roof structure. Additionally, success has been achieved with experiments to compensate for human motion and hold the end effector at a constant position. It can easily be imagined that the possible uses will only continue to increase.
Bibliography


