Table of Contents

Executive Summary

This report describes the details of a robotic vision platform to be implemented on a bipedal robot designed by the Institute of Machine Human Cognition (IHMC). This design is the third iteration of a vision platform that is intended to provide image stabilization during operation, as well as telepresence with the potential for object recognition. The design will explore 3D vision and significantly decrease backlash when compared with the previous designs. Vision in 3D will be implemented with the addition of 3D goggles as well as testing two methods of achieving stereovision. Two different methods of obtaining 3D vision will be implemented in the design: a binocular camera system (Bumblebee2) and two discrete cameras (Fire-i). The platform is a 2 degree of freedom system controlled by two geared DC brushed motors to provide sufficient stabilization. Two sets of synchronous belts and pulleys are implemented to transmit power. This vision platform is light and accurate and will enhance the functionality of the biped.

Introduction and Motivation

Bucknell University, in conjunction with the Institute for Human and Machine Cognition (IHMC), is developing a bipedal robot designed to operate in an urban environment. Currently, the biped consists of a torso with two human-like legs. A senior design team has been assembled to develop a robotic vision platform (RVP) for this bipedal robot in order to provide telepresence to an operator and with the capabilities for 3D mapping in the future.

Background Research

A number of specifications and design considerations of the robot head have been influenced by existing robots. Two of the robots researched were MERTZ, and Robonaut. From this research two vision platforms were developed during the summer of 2009. These platforms were designed in parallel, one by Matthew Kandler and Daniel Snyder and the other by William Rittase and Henri Sirot. These designs have been utilized to provide insight into the next iteration of the vision platform. Continuing from these designs, research was focused on three-dimensional vision and mapping along with refining the actuation transmission system.

Robotics Industry

MERTZ

The MERTZ head was designed by The MIT Computer Science and Artificial Intelligence Laboratory for analyzing social behaviors (Figure 1). It requires continuous unattended operation interacting with humans for extended periods of time. By interacting with humans it can identify and correlate objects and people and observe people's habits. MERTZ can even learn to dislike people that annoy it. The functions of the MERTZ robot vision head are far beyond the scope of this project at this time. The IHMC biped only requires stabilization and vision from this design. Perhaps, in the future this type of vision platform will be necessary for the IHMC biped to interact appropriately in an urban environment. Because the functions of this robot head are more involved than what this project hopes to attain, the size and weight constraints of the MERTZ robot were referenced as maximum values.

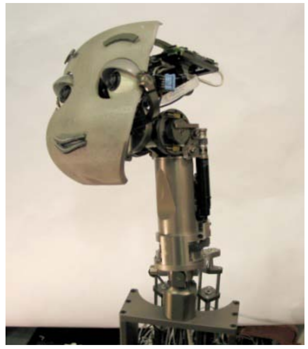


Figure 1. MERTZ Robot Head

Robonaut

Robonaut was developed by NASA in conjunction with Defense Advanced Research Projects Agency or DARPA (Figure 2). It is intended to be implemented in space missions. This robot is more similar in function to the biped developed by IHMC. One important distinction is that Robonaut is a wheeled robot (similar to a rover) and thus does not have many of the constraints required by a bipedal platform. The biped has strict weight requirement and requires much more stabilization than a wheeled robot. Many of the specifications for the cameras used by Robonaut were not realistic for the RVP due to their large size and weight. However, the robot's head is intended to provide telepresence to the operator and move much like a human head would. Because of the similarities in function, the research that the designers of Robonaut conducted for the motion of the head was helpful in the design of the IHMC robotic vision platform.

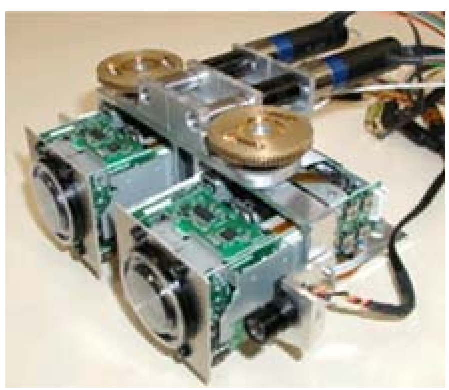


Figure 2. Robonaut Robotic Vision Platform

Initial Designs

Based on existing robots, Professor Shooter and the engineers at IHMC developed a list of requirements for the initial designs. Both of the designs developed during the summer of 2009 were two degree of freedom systems. They each used two brackets to move the cameras along the pan and tilt directions, aligning the vision axes with the centers of rotation. These designs were fitted to mount Point Grey Firefly MV cameras. However, the motor selection and size for each design varied greatly. The goal of these designs was to provide vision platforms that could be tested, modified, and further built upon.

Vision Platform Design 1: Kandler and Snyder

The platform designed by Kandler and Snyder was designed to test the speed and acceleration requirements for the head. It is a one-camera system that utilizes two geared DC motors with optical encoders for position feedback. The platform was designed to be as simple as possible. The pan and tilt directions each had an aluminum bracket that attached to a motor directly by a screw clamp.

The motors and encoders were powered by and controlled with a PC/104 board that was able to integrate into the computer on the existing bipedal robot. The controls were also integrated into the existing biped controls which allowed for active stabilization from the biped's onboard gyroscope. One of the benefits of this aspect of the design is that the PC/104 could be used to power the motors of future designs. With minor adjustments in the code to account for new encoder resolutions and gearing, the same program could be used to run the next design.

This head was eventually mounted on the biped in the IHMC lab (Figure 3). After running several tests on the active stabilization it was found that the speed and acceleration were more than adequate to stabilize the camera during motion. One of the primary concerns with this design was backlash in the motors. Though the testing proved that the stabilization was sufficient, there was still some backlash in the gearheads, which were mounted on the motor by the supplier. According to the specifications of the gearheads, there was up to 3° of backlash. This meant that position of the camera could never be accurate to within 3°.

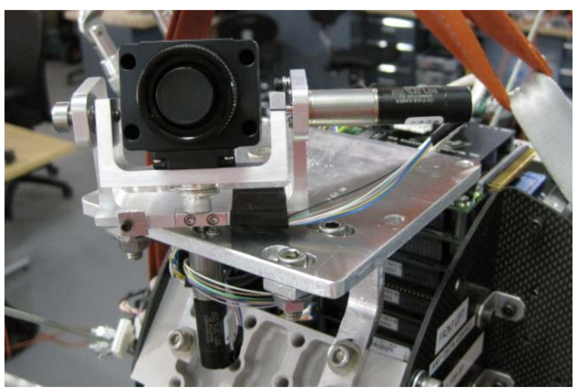


Figure 3. Kandler-Snyder RVP

Vision Platform Design 2: Rittase and Sirot

The platform developed by Rittase and Sirot used RC servo motors as the primary actuation instead of the DC brushed motors used in the Kandler-Snyder design (Figure 4). These motors were given commands to go to an exact location by pulse width modulation and therefore did not require any positioning feedback device such as an encoder. A joystick was used to control the position of the camera system.

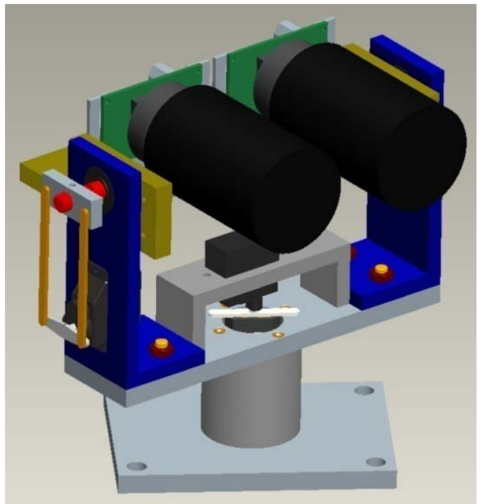


Figure 4. Rittase-Sirot RVP

Two support brackets allowed for the head to move in both a pan and tilt motion. In order to accurately balance the moment of inertia, the camera mount had slots to manually balance the system by varying the position of the two cameras (both Firefly MVs). This helped in the motor selection. The team could accurately position the center of mass at the axis of rotation to decrease the torque requirements on the motors. This also put less axial load on the motors once the power was turned off.

This system performed adequately but was also hindered by the backlash experienced in the pan and the weak tilt motor. Since the plastic shell casing was not included in motor sizing calculations (removed in the figure above), the specified tilt motor was not able to provide enough torque. The motion of this sytem was not smooth enough due to the discrete nature of servo motors, and, even when more powerful motors with metal gears were used over their plastic-geared counterparts, the backlash was still slightly too high to meet project requirements.

The motion transmission system differed from the Kandler-Snyder design which had its motors directly connected to the axis of rotation. This design had a push-rod system to move the tilt actuation away from the center of rotation. Therefore, there was not a motor hanging off the side which may have gotten in the way of a shell or helmet. In addition, the motor was moved closer to the pan axis of rotation, decreasing the moment which the pan motor was required to accelerate.

Three Dimensional Vision

Two methods of creating stereo vision emerged from research performed over the summer of 2009, one of which is a single, integrated camera system while the other is the combination of multiple, discrete cameras (Appendix I). Both of these solutions were purchased from Point Grey Research (PGR) before the start of the semester. The team worked through April under the assumption that these cameras would be implemented in the design. It was later found, however, that due to inconsistencies with Point Grey software and the image format they output, it would be impossible to use two Firefly MVs to obtain a 3D image with the Stereoscopic Multiplexer and Player. In place of the Firefly MVs, two Unibrain Fire-i cameras were purchased. The three camera systems are briefly mentioned below, and the decision between them will be discussed in detail in the Electrical Implementation section.

The first system is called the Bumblebee2 and is an integrated system that contains two cameras mounted in a single case that is calibrated for 3D vision and mapping (Figure 5). It is a comprehensive solution that includes software for camera control, image rectification, 3D point mapping, object tracking, and multi-camera integration. The sufficiently high resolution and frame rate meet the engineering specifications for the vision system. Its main drawbacks are its relatively high weight (0.75 lb), large size (6.2 in long), and unknown capability to create a 3D video output signal.

In addition to the Bumblebee, two Firefly MV cameras were included in the design to create a stereo image (Figure 5). This would require the team to correctly align and calibrate the image, which would only be used for 3D video output to an operator. However, the Firefly MV is small (1.7 in wide), light (0.08 lb), and is able to see Infrared light if a filter is removed.

Figure 5. Bumblebee2 Camera

Figure 6. Firefly MV Camera

Unibrain's Fire-i cameras were chosen in the final weeks of the project as a back-up solution (Figure 7). They have similar resolution (640x480) and form factor to Point Grey's Firefly MVs, but are slightly larger(62 x 62 x 35 mm, 60 g). The team will use two cameras to create a stereo (3D) image. This camera, however, will work with the software to stream two live cameras simultaneously because of the different signal output. The presence of 2 FireWire ports per camera is an additional benefit that allows them to be daisy-chained together.

Figure 7. Fire-i Camera

Three Dimensional Display Systems

In order to output a three-dimensional image to a human operator, multiple types of 3D displays were investigated. The most widely used method to display 3D video is through the use of vision goggles that fit over the users head. These use two small display screens to provide each eye with a slightly different image, creating the appearance of a single image with depth. Most models are expensive and offer a limited field of view (Appendix I). The best combination of price and performance was found in eMagin's Z800 stereo vision goggles (Figure 8). These lightweight (8 oz) goggles have high resolution (800x600) OLED displays, a 40^{o} field of view, built in 3-axis head tracking (for movement of the RVP corresponding to the operator's head position), microphone and speakers, and relatively wide compatibility with graphics cards. They require frame-sequential video input via a single VGA cable. These goggles were ordered for $1299.

Figure 8. eMagin Z800 Goggles

Figure 9. iZ3D Monitor

Another option to display a 3D image is the use of special 3D computer monitors or TVs (Figure 9). Although the technology is less well known, it has been around for about 5 years and is finding increasing market use. Most versions require users to wear either passive polarized glasses or active shutter glasses, while some screens need no eyewear but do require observers to be in specific viewing positions. The most promising setup is made by iZ3D Technology; its 22"

LCD monitor has a second polarizing screen overlaying the normal LCD, thus creating an image that is seen in 3D when the user wears passive polarized glasses. The $300 iZ3D monitor is also compatible with the Stereoscopic player, and could be considered as a way for a group of people to watch a 3D demo simultaneously.

Customer Requirements and Engineering Specifications

As mentioned previously, the goal of this project is to develop a robotic vision platform for a bipedal robot that will operate in an urban environment (Figure 10). Since the torso and legs of the robot are already constructed, the platform needs to be able to integrate with the rest of the biped. Based on work conducted on the previous iterations, our primary focus for this iteration is to minimize the backlash between the motor and gearhead as well as in the transmission of power from the motor to the bracket.

The vision of the human head is capable for rotating along three axes of rotation, the pan (motion of head shoulder to shoulder), the tilt (nodding of head up and down) and the yaw (twisting the head). In order for the robot to have an acceptable range of vision, it was determined that pan and tilt motion are necessary. A third axis of rotation, or the yaw motion, however, was determined to be unnecessary. Additionally, it has been difficult to determine the best way to obtain 3D video between the 3 camera systems. Therefore, the design is versatile and is able to implement multiple systems using a standard photographic screw attachment. The design of the platform should be as light as possible in order to reduce the torque requirements and size of the motors on the head, as well as the rest of the body. Also, there are several electronic components that will be placed on this platform so locations and paths for the wiring need to be considered during the design process.

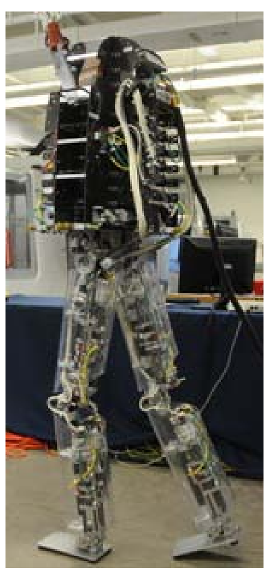


Figure 10. IHMC Bipedal Robot

In order to facilitate and guide the development of the RVP, the project's advisor, Professor Steven Shooter, required certain deliverables through all stages of the design process. The following is a list of all items to be completed by the end of the project.

- Comprehensive review of web and other literature on the design and development of robot vision platforms
- Development of detailed design specifications
- Development of several conceptual designs of potential vision head configurations
- Theoretical and computational evaluation of vision platform concepts
- Selection of the concept and detail design of all components, including drawings of all parts, selection of sensors, and specification of elastic components
- Purchase of vendor supplied components
- Fabrication of remaining components
- Assembly of the vision platforms
- Formulation of testing procedures and comprehensive testing of performance;
- Refinement of design to improve performance
- User's manual, video of performance of final design, and recommendations for further improvements to the design
- Regular communications and updates to IHMC researchers
- Complete and detailed project reports at the conclusion of the fall and spring semesters

Each of these requirements has been completed. The team researched several heads from other robots and gained significant insight into the state-of-the-art robot heads. Design specifications have been intricately tuned by the team throughout the year based on the previous head specifications and the successes and failures of each design. Additionally, each of the specifications had a corresponding validation technique for when the final prototype has been constructed. The group modeled several different vision platform concepts in SolidWorks and evaluated their operation and performance as well as selecting the appropriate hardware for each. A design was selected from this process and the first iteration of the RVP has been fully designed.

Fabrication of the RVP occurred in the second semester. During the fabrication of the design modifications were made and are documented in the Discussion section of the report. Testing procedures were created after assembly and these procedures were performed and can be found in Testing Procedures.

The team met weekly with the project advisors to discuss progress and determine goals for the coming week. Meetings with the team members at IHMC are not as frequent but a couple teleconferences have occurred during the course of the project.

Requirements

Beginning on the 20th of April, 2009, and updated through the 29th of May, 2009, a list of requirements for the head was compiled by Professor Steven Shooter (Appendix II). Though these requirements were determined by a group of individuals from IHMC with significant experience in both the robotic and design fields, this list was vague in terms of numerical requirements. From these requirements, the team developed a list of potential scenarios that the robot may encounter to give insight on defining some of the specifications.

List of Required Scenarios

- Navigating safely through an urban environment
  - Have a large enough range of vision to identify and avoid hanging objects, steep ledges etc
  - Avoiding walking into walls, windows, and screen doors
- Going through a standard door (~35" x 83")
- Going up and down stairs (rise 6"-9.5")
- Walking up and down sloped surfaces
- Gracefully walking over rough terrain*
- Dynamically walking and balancing*
- Recovering from a push*
- Identifying and avoiding moving hazards (something rolls or moves in its path like a dog or car)
- Stepping over low obstacles (door jams and curbs)
- Interpreting and adapting to ground surface (grass, concrete, carpet, tile etc)
- Seeing in color

List of Potential Scenarios

- Navigating in low or no light
- Navigating in extremely bright light
- Navigating in low visibility (such as fog, or smoky rooms)
- Seeing in 3-D
- Recording of visible history
- Obtaining audio feedback
- Operating in extremely high or low temperatures
- Operating in radioactive, and/or chemically or biologically hazardous environments
- Identifying traffic lights, and other street signs
- Running, jumping
- Ducking

*IHMC identified these requirements in the paper "Design of a Bipedal Walking Robot" (Appendix III)

Additional Requirements from "Design of a Bipedal Walking Robot"

- Mechanically and electronically robust (mean time failures of several months)
- Real-time feedback
- Easy to write, compile, download and run software
- Easy to run and maintain, able to operated by single person
- Robustness to disturbances

By identifying the potential scenarios that the robot might encounter, the team was better equipped to specify the constraints on the design.

Specifications

Given these requirements at the start of the project, information from the previous designs, and feedback from Dr. Peter Neuhaus at IHMC, the Robotic Vision Platform Team generated a list of engineering specifications (Table 1).

Table 1. List of Specifications

Specifications	Value
Size	smaller than 8”x8”x 10” (DxWxH)
Weight	4 pounds
DOF	2
Speed	200 rpm
Acceleration	1800 deg/s^2
Accuracy of Positioning	Less than 1^o
Encoder Resolution	.01^o
Range of Motion	180^o pan, 150^o tilt
Number of Cameras	4
Camera Frame Rate	30 frames per second
Field of Vision	60
Resolution	640 x 480

Most of the requirements defined by the IHMC researchers identify the specifications of cameras to be implemented in the design, such as frame rate, resolution, etc. The initial camera systems (Bumblebee2 and Firefly MV) were purchased using these specifications in the summer before the team was put together. Therefore, the team largely focused on the size, weight and backlash of the actuation transmission systems. The vision platform should be small and lightweight to minimize power requirements, and the speed is intended to mimic the speed of a human eye. The most important specification at this point in the project is the accuracy of positioning and stabilization of the camera system, which will be primarily dictated by the backlash or “play” in the transmission system.

The speed of the motors needs to be fast enough for the image to be actively stabilized. The biped has significant movement in its torso while walking due to a lack of any actuation in the torso. It would be nauseating for an operator to deal with such large translations in the camera, so the motors will use feedback from the biped’s on-board gyroscope to help compensate for this movement. The previously built vision platform by Kandler and Snyder was able to attain speeds up to 1200-1300 degrees per second. This exceeds the speed of a human eye, which is approximately 800 degrees per second. The Kandler and Snyder platform was significantly smaller, it only carried one camera, but this design will aim for similar speeds. It will need to be at least fast enough to actively stabilize the image. This number was intended to be refined when the previous designs could be tested to accurately determine their speeds. However, due to issues with setting up the PC/104 stack we were not able to do any significant testing of the previous iterations.

Accuracy of positioning is particularly important for the vision platform. Any play in the motors will cause unstable images and inaccurate positioning. This error will propagate through the stereo vision algorithms creating error in the position of the physical objects. In addition, the image platform will shake while walking, causing discomfort for the operator. Because of this, the accuracy of positioning was specified to be below 1 degree.

Minimizing weight is another important design consideration. IHMC has asked that the total weight of the head be kept to no more than about 4 lbs to reduce the load on the body. The Bumblebee2 and two Firefly MVs that have to be attached to the head have a combined weight of .832 lbs, leaving about 3 lbs for the metal framework, motors, shell, and Firefly camera lenses. Keeping the actuated mass at a minimum will reduce the load on the actuators, thus allowing for smaller motors and an overall lower weight. This will also help to improve the speed and accuracy of head motion.

In addition to maintaining a low weight, the vision platform should also be small and humanlike in shape. A human head is approximately 7.4” high and 5” wide. The specification determined for this platform is to fit within a box 8” x 8” x 10”. This is much bigger than a human head to account for the wide shape of the Bumblebee2 and also to include room for the electronic equipment.

Additional information on the justification and plans for validation of the specifications are attached (Appendix IV).

Concept Design and Evaluation

Design of the RVP was broken down into two major phases. The first phase was to determine the type of transmission that would be used to drive the pan and tilt of the head and the second phase was to find the best means of implementing the transmission system with the least amount of play.

Transmission System

Since pan and tilt were determined to be the only two necessary degrees of freedom the first design aspect was determining how to actuate the head in each of these axes. A variety of transmission systems were explored to find which would be most appropriate for the head based on the design specifications. After creating rough design concepts to go with each of the proposed transmission systems, comparing characteristics using a datum decision matrix, and thorough discussion, a transmission system was chosen.

Worm Gears

One of the first options explored was worm gears. A major benefit is that worm gears are not backdriveable. This would also save energy because the motors would not have to work to hold the cameras at a specified position. Additionally, the worm gears are capable of producing large gear reductions. This would eliminate the need for a gearhead and reduce weight and size of the head. The backlash on worm gears can be as small as 1’ 2” arc-min/sec (approximately .017 degrees), which is well within our specification of 1 degree. Unfortunately, in order for such low values of backlash to occur, the machined mounting positions would have to be extremely precise. Any small misalignment could completely negate the effects of the low backlash gears.

Cable Drives

A more robust transmission option was the cable drive. Depending on the material of the cable, the drive could handle extremely high torques, up to 76,000 lb-ft. Since the cables are a flexible material, the position of the drive has much more freedom than a traditional gear set. In addition to their flexibility, cable drives have extremely low backlash as long as they are properly tensioned, they do not require as precise alignment because of the tensioning in the cables. Though cable drives minimize backlash, they are not able to provide significant gear reduction without sacrificing size. This could be rectified by using a gearhead on the motor. Another concern with the cable drives is that the tension on the pulleys needs to be accounted for when designing the shafts for the drives.

Belt Drives

Timing belt drives were also considered as a potential transmission system. Timing belts, like cable drives, minimize backlash without requiring high machine tolerances. Belt drives are used in many rapid motion applications such as printers and laser cutting machines. A benefit of belt drives is that the belts and pulleys can easily be purchased in standard sizes. One issue is that the head assembly must be considered while designing in belt drives. Belts cannot just be wrapped around the pulleys after the head is complete; they must be properly tensioned during assembly.

Big Gears

The “big gears” transmission concept involves a small gear on the motor shaft driving a much larger gear on the camera mount. This would result in a large gear reduction and the size of the big gear would determine how far away the motor axis could be placed from the axis of rotation. The size of the gears, however, would increase the weight of the head. Much like the worm gear transmission, the “big gears” concept requires high precision for the machined parts.

Evaluation

The decision came down to a few main factors which were placed into a datum design matrix (Table 2). The worm gear was the datum, or the standard by which the other forms of transmission were compared. Some of the major concerns with the transmission system were weight, backlash, and difficulty of assembly.

Table 2. Datum Analysis

Criteria	Worm Gear	Cable Drive	Big/Small Gear	Series of Gears	S.E.A.'s	Push Rods	Belt Drive	Bevel Gears
Low Weight	0	0	0	0	-1	1	0	0
Low Backlash	0	0	0	-1	1	-1	-1	0
Size	0	1	-1	-1	-1	1	1	-1
Ease of Assembly	0	0	1	0	-1	-1	0	0
Range of Motion	0	0	0	0	-1	-1	0	0
Complexity	0	-1	0	-1	-1	-1	1	0
Machinability	0	-1	0	0	-1	-1	0	0
Adjustability	0	1	0	0	0	1	1	0
Distance From AoR	0	1	0	1	1	1	1	0
Gear Reduction	0	-1	0	-1	0	-1	-1	-1
Transmission Losses	0	1	1	0	1	1	1	0
SUM	0	1	1	-3	-3	-1	3	-2

*SEA: Series elastic actuators

After analyzing the datum decision matrix, the four highest transmission systems were further compared (

Table 3). In the conception of the design, the primary concern was the amount of backlash that the transmission would introduce into the system. Thus, the table assessed backlash, torque, typical applications and a summary of other notable qualities.

Table 3. Transmission Analysis

	Torque	Backlash	Applications	Summary
Worm Gear	limited to 750 hp	Range 1’ 2” to 28’ 48” arc – minutes	Differential systems in cars, milling operations, toys and small electrical operations	• High gear reduction • Heavy • Requires high precision • Noisy at high speeds • bulky
Cable Drives	Up to 72 lb-in for single wrap cable drives For multiple cable drives range to 76,000 lb-ft	minimal	Silicon wafer saws, positioning units for directional solar panels and robot arm joints	• Moves actuation away from axis of rotation • Eliminates backlash • Work equally as well as speed increasers or decreasers • Requires tension • flexible
Belt Drive	limited to 200 hp Small maximum gear ratio (about 10:1)	minimal	Power saws, motorcycles, vacuum cleaner brushes, printers, laser cutter	• Requires tension • Thin, flexible (allows them to operate well on miniature drives and in apps requiring high speeds or small pulleys) • Maybe the most efficient form of power transmission short of direct drive • Can sustain high loads • Low precision required • Easy calculations
Big Gears	Really high	Anti-backlash gears have backlash of 1-3 arc-min	Clocks and watches, washing machine, pretty much anything…	• Requires high precision • Highest torque capability • High gear reduction • Heavy • Unlikely slippage • Noisy at high speeds • bulky

After analyzing backlash of the various types of transmission, it was noted that backlash was not an issue for any of the transmission systems. Each of the options could have very low backlash, if properly designed. The “big gears” and worm gear options, however, would require much more precise tolerances and assembly to reduce backlash.

The belt and cable drives would be the most ideal choices in terms of weight. Belts and cables would have comparably negligible weight and pulleys would not be nearly as heavy as the gears used in the other options. Belts and pulleys also make the layout of the design much simpler because they can be mounted further from the axes of rotation without adding significant weight and thus altering the center of gravity. Cable drives are very useful for specific applications but are complicated to machine and design. For these reasons listed, the belt drive was determined to be the preferred method of transmission. The main concern however, will be to find a way to properly tension the belt.

Concepts

The next step was to start exploring implementation of the transmission systems. Though there are an infinite number of solutions to the design problem, in order to maintain reasonable specifications and performance two primary concepts were seriously considered.

Cameras

It was determined that both the Bumblebee2 and the Firefly MV cameras would be used on the robotic vision platform. This would allow the RVP to have a degree of modularity through the use of standard photographic mounting screws. The Bumblebee2 could be used to perform 3D mapping and the Fireflies could be used for telepresence. Ideally, the Bumblebee2 could be used for all the desired functions of the head but there were concerns with how much the camera could handle and how the data would be split up to perform multiple functions. Additionally, the Fireflies can be placed at a distance that models the human eyes and results in a more natural feeling telepresence. Both cameras will be designed into the RVP but in a way that they could be removed if not needed. This will provide the option of reducing weight once the capabilities have been fully tested.

Simple Rotation

Simplicity is often times the best approach. The simple rotation concept has a pan bracket and a tilt bracket that are both being rotated about the axis of vision (Figure 11). This is preferred because the cameras will not be translating at all during motion, just rotating.

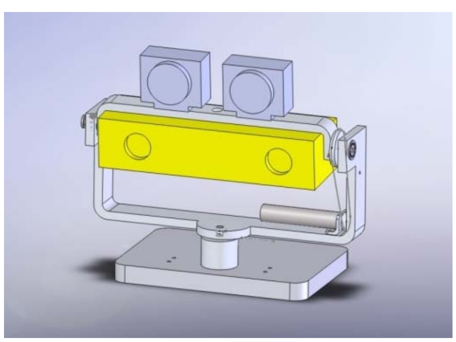


Figure 11. Simple Rotation with both Bumlebee2 and Firefly MVs

Due to the simplicity of the design, there is also a large range of motion allowed by this design. The camera will easily be able to move 135° in the tilt and a full 180° in pan. By rotating the head about the vision axes there is also the potential to perform balancing such that the rotation axes are collinear with the center of gravity. This would greatly reduce the moment of inertia and decrease energy requirements.

One of the issues with this concept is that the tilt motor must be attached to the pan axis. Thus, the pan motor must be able to drive the weight of the tilt motor and the wires will not be stationary coming from the tilt motor. Also, the cameras will not be able to see the feet of the biped. By looking directly down and not moving forward, the cameras would be looking into the body of the biped rather than at the feet.

Neck Joint

The "neck" joint is a more anthropomorphic approach to the conception of the robot head. There are a few major benefits of this design. The neck lifts the head above the axis of rotation which would allow the head to move forward while looking downward and possibly be able to view the feet of the biped.

There are two potential concepts of the neck design. One of these designs (Figure 12) allows for parallel motion of the head which means that the pan and tilt motors could both be mounted on the stationary part of the head. Since neither motor would be moving the other, the motors could be sized down. This would make the wiring of the motors much simpler as well. The camera platform would also allow for easy attachment of a shell or helmet. The platform has plenty of mounting space and does not interfere with other parts as much as the other design.

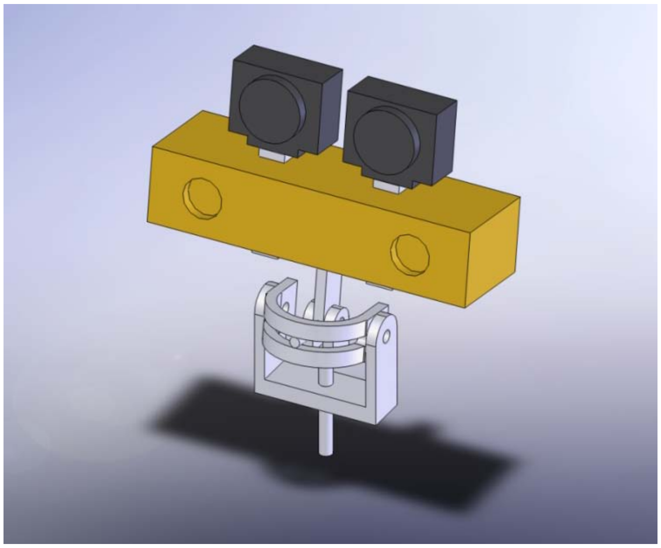


Figure 12. Neck Joint Concept 1

The second neck design (Figure 13) was ultimately rejected for a couple of reasons. First, this neck does not have the parallel drive benefit that the first neck concept has. This would significantly increase moment of inertia and weight of the motors. Since weight is a driving factor for the design this was a strong reason not to pursue the concept any further. Additionally, there is an issue with the angle of vision. Ideally the cameras should be able to look around their range of motion while maintaining an image that is parallel to the ground. However, the second concept performs tilt before pan; if it were to tilt down and then pan to the side there would be unwanted rotation of the image.

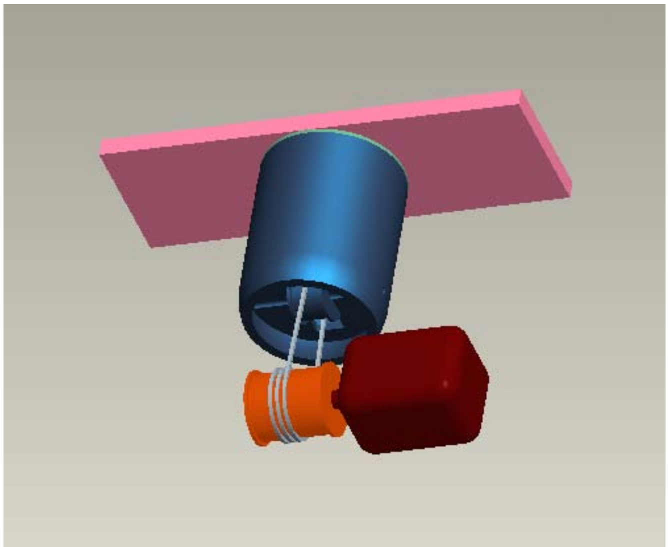


Figure 13. Neck Joint Concept 2

A major disadvantage of the neck concept is that the moment of inertia is greatly increased by moving the cameras off of the rotational axes. This would increase the power required to move the head and call for larger motors. It needs to be determined if the increased size of the motors to account for the larger moment of inertia would increase the overall weight of the head beyond specifications. Another disadvantage is that the neck has a limited range of motion. When the tilt axis is placed below the pan axis, the camera can only look up or down directly in front of and behind the torso; it cannot look sideways and down. The current design cannot move the full 90° in either direction in pan or tilt. Design adjustments may eliminate this issue.

Evaluation

Each of the design concepts has obvious advantages and disadvantages. While the simple rotation design has a much greater range of motion and a low moment of inertia, there are issues with the wiring, mounting a helmet, and one motor must be strong enough to move the other. The neck design would have no major wiring issues, would allow the head to see the feet, and the parallel drives would reduce weight; but there would be weight issues with the long moment arm and the range of motion would be limited.

Ultimately, the simple rotation design was chosen. After a discussion with the leading engineers at IHMC, it was determined that the advantages of having a neck joint did not warrant the increased complexity. The ability to see the feet from the head is not of substantial importance at this time. If the operator does need to see the feet, this issue will be resolved by placing a camera at the waist of the robot. The wiring issues associated with the simple rotation design will be addressed by implementing a hub so that all electronic equipment will be centralized. Because the motors that were specified are very compact and lightweight, the ability of one to move the other is not as much of a concern as originally theorized. Thus, the simple rotation design should be able to combat all of the major concerns and be able to meet all of the previously identified specifications.

Design Embodiment

The final design for the simple rotation concept required some modifications to ensure the achievement of every specification (Figure 14). There were two brushed DC motors geared down and attached to timing belts that rotate each axis. The addition of a helmet was also included in the design (Figure 15).

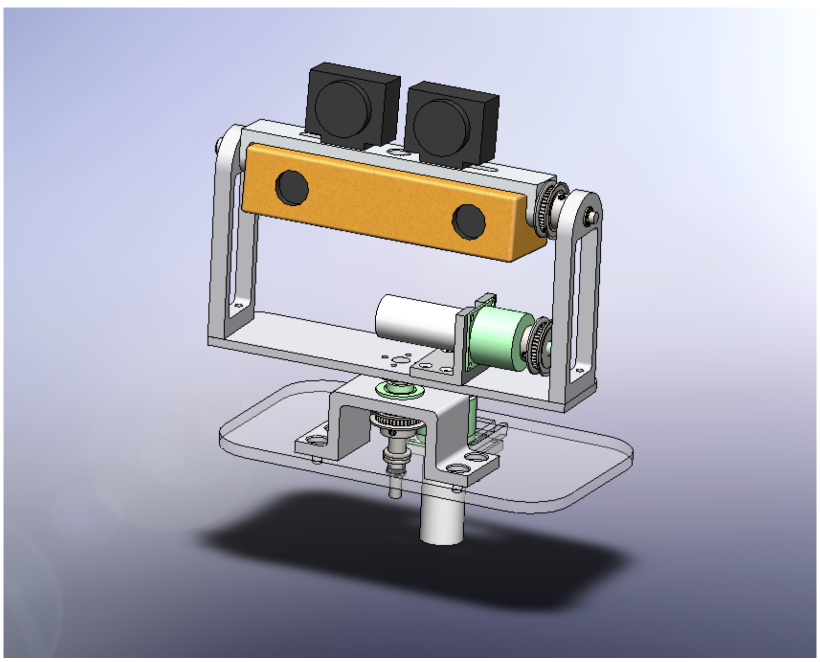


Figure 14. Final Design of RVP without helmet or wiring

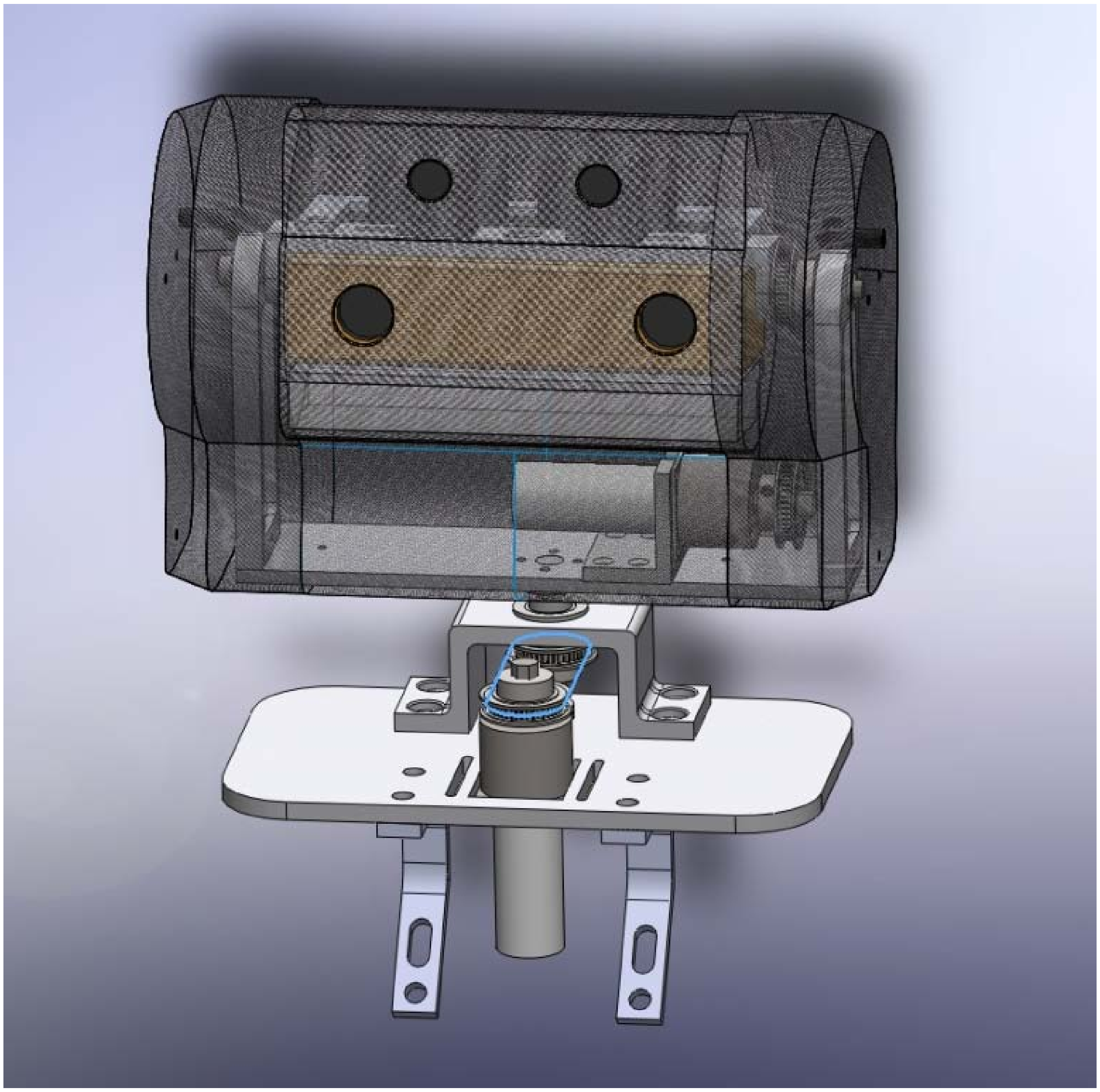


Figure 15. Final Desing of RVP with helmet and wiring

As discussed in the Concept Design and Evaluation section above, backlash and position accuracy were the extremely important. Thus harmonic gearheads, which were accurate to 1/30th of a degree, were chosen in tandem with Micromotor DC motors. There will be a hand machine piece that will mount the two pieces. GT2 belts were employed to transmit the power and keep the backlash low. These components are discussed in detail in the Component Selection Section of this report.

Key Design Decisions

- **Pan Bracket** – The pan bracket was determined to be a u-shaped bracket composed of three individual plates. This design was chosen for a couple of reasons. A large, single-piece bracket would require a large block of aluminum and waste most of the material.

Any large force on the arms could cause bending and lead to misalignment of the holes for the tilt shaft and require replacement of the bracket. In addition, assembly could prove difficult. A three-piece bracket allows for much easier assembly because the arms can be attached after other components. If either arm were to bend and require replacement, it could easily be replaced. Also, if the team decided to change the tilt bracket (if the camera layout were changed, for example) the arms could be switched out. This design enhances the ability to improve and iterate on the head.

- **Tilt Bracket** – The tilt bracket was constructed to fit a BumbleBee2 and two Firefly MV cameras. To allow for adjustability the Fireflies were mounted to slots. The ideal distance between the cameras is not yet known and needs to be tested by using the slots to adjust the cameras to optimize the distance for 3D vision. Additionally, the dimensions of the tilt bracket were refined to minimize the moment of inertia. The length of the sides was adjusted to set the center of gravity about the shaft holes.

- **Motor Slots** – Proper tensioning of the belt drives was important. In order to achieve tensioning, slots are included for the motor mounts. Sliding the motors will provide an easy way to tension while maintaining alignment.

- **Tilt Shaft –**The tilt axis was divided into two sides: the drive side and the supporting side. The supporting side of the tilt axis was constrained radially using a shoulder bolt and flanged ball bearings. Shoulder bolts were precision machined to improve alignment. A stainless steel shaft was to be press-fit into the other side of the tilt bracket. This, however, was changed during fabrication and is addressed in the Discussion section. This shaft had a pulley attached via set screws on a 1mm deep groove. The other end of the shaft slides through two flanged ball bearings on the pan bracket arm. To axially constrain the shaft, two snap rings were placed in circular grooves on either side of the flanged bearings.

- **Pan Shaft** – The pan shaft was attached to the bottom of the base of the pan bracket by a hole and flange. Alignment was achieved by fitting the top of the shaft into a hole and then it was held in place by four screws on the flange. The pan shaft carries the load of the entire head and it was important that this shaft was properly constrained. In order to handle both radial and axial loads, a combination of ball bearings and a thrust bearing was used. A support bracket was used to eliminate moment produced by loading from the pulley placed in the middle of the shaft. Flanged ball bearings are used in this support shaft and base plate. There was a shaft diameter reduction at the end of the shaft that allowed the shaft to rest on a thrust bearing to handle axial load. To account for any axial load pulling up on the head, a snap ring was placed beneath the flanged bearing in the base plate. During fabrication, it was determined to completely redesign this mechanism to accommodate wiring and electrical components. Please see the Discussion section for more detail.

The final design was drawn in SolidWorks. An example drawing file is attached below (Figure 16) and the remainder of the drawing files can be found in Appendix V.

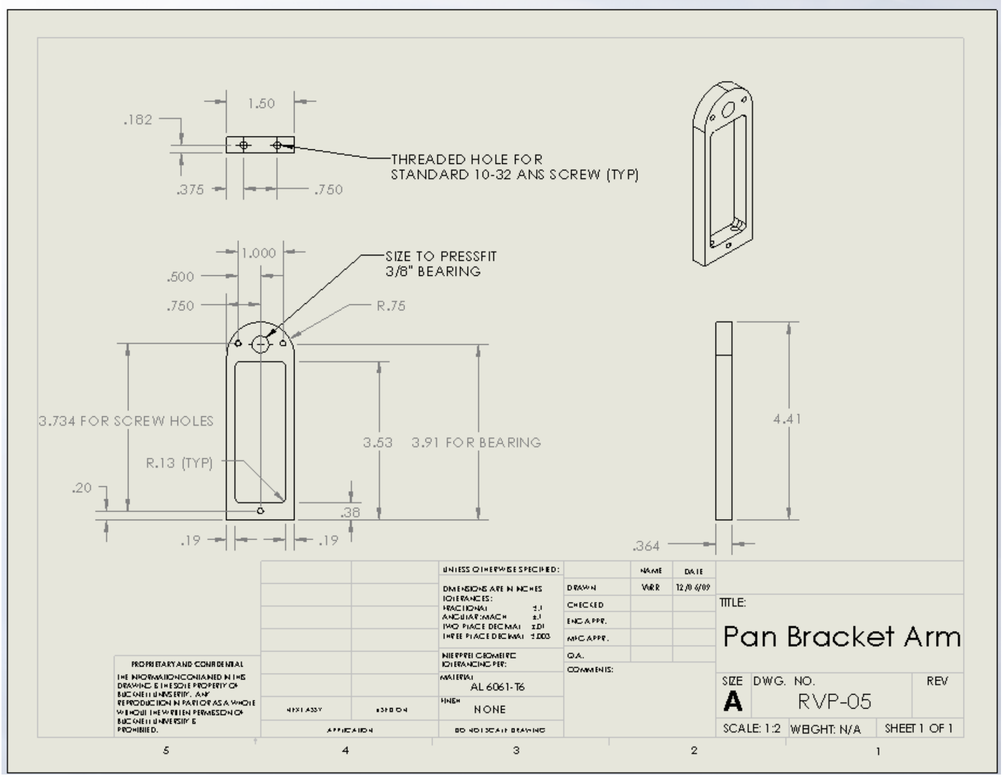


Figure 16. Pan Bracket Arm Drawing

Shell Design

The design of the “shell” or outside covering of the head went through a number of concepts to find the best combination of low weight, small size, functionality, aesthetics, and manufacturability. Initial designs attempted to cover the whole moving portion of the head in a single casing that would both pan and tilt. One concept attempted to follow a relatively anthropomorphic shape that kept the surface of the covering close to the cameras to reduce size and increase field of vision (Figure 17). However, a large circular radius was required at the bottom of the shell to allow a full range of tilt motion, thus making the design large and unsightly. Another concept avoided the issue of the shell intersecting with the inside brackets by making the shell a complete sphere. A clear plastic or glass shield placed on the front allows the cameras to see. This design, however, required the whole shell to be as large as the radius from the tilt axis to the bottom of the pan bracket, thus making it unnecessarily bulky. The clear shield would also be very difficult to keep optically clear and could bend the image (Figure 18).

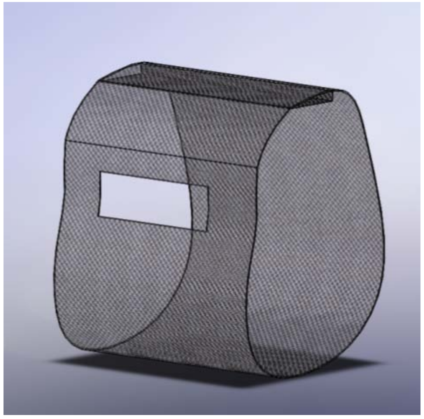


Figure 17. Anthropomorphic Shell

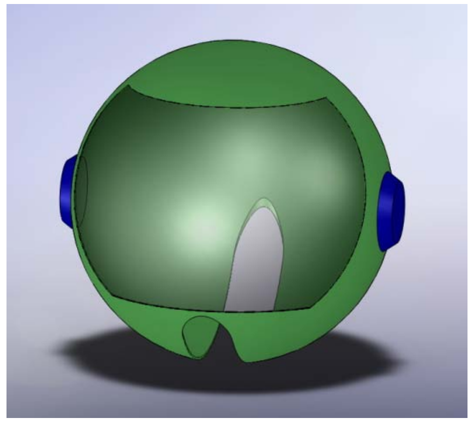


Figure 18. Spherical Shell

A third design took both of these into consideration. Both of the camera systems would have a hole directly in front of the lens to give the appropriate vision. There was an inside covering over the cameras which tilts independent from the outside housing which is connected to the pan. The issues with this were in the separation between the tilt/pan housings. There is room for fingers or other objects to get caught when in operation. In addition, the lenses are exposed to the environment; since they are the most important parts to the vision aspect of the project, they must be protected. It also looked rather odd as far as aesthetics were concerned (Figure 19).

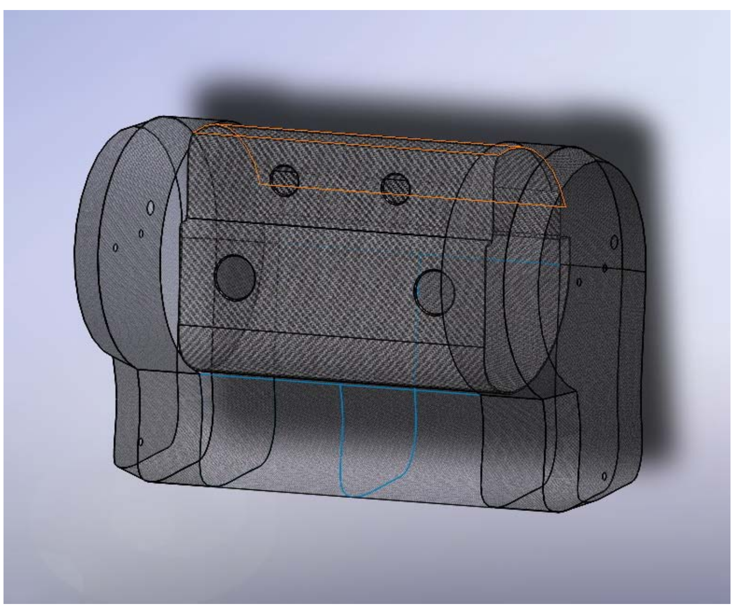


Figure 19. Semester 1 Final Design

The final design was much simpler than the previous design. The result was a fixture which moved only panned. This removed of the possibility for the tilt to interfere with the pan. In addition, it added to simplicity of removal of the shell from the head, to be able to easily access the hardware underneath the shell. In addition, the ease of manufacturability and assembly of the shell was integral in this design. There was only one front and one back which attached to the pan base. In order to remove it, one simply needed to unscrew a couple of bolts. In previous designs, such as in the summer of 2009, the shell was difficult to detach which maintenance time consuming and frustrating.

In the final design there were two simple plastic coverings over the cameras which spanned 150 degrees so the cameras could tilt and still see outside the shell. This covering is not spherical and therefore could not distort the image (Figure 20).

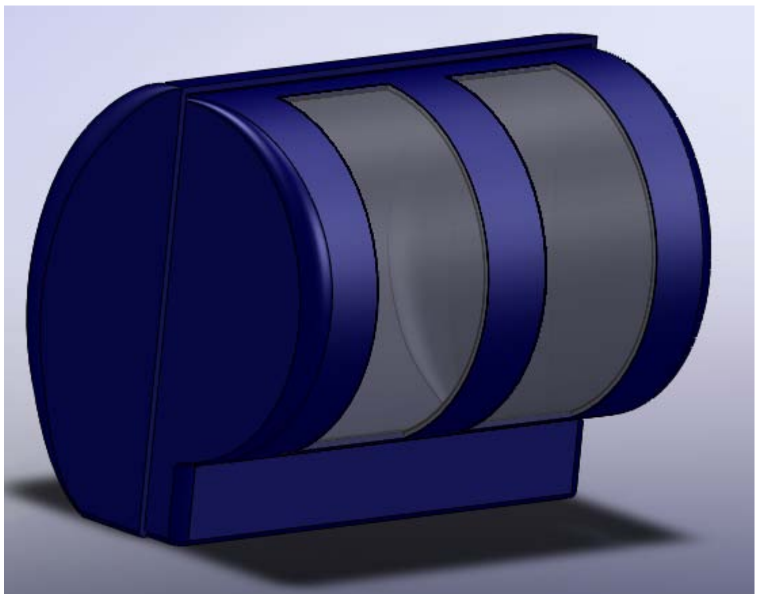


Figure 20. Final Shell Design

The shell was also made of fiber reinforced plastic and designed as small as possible to decrease weight and size. In order to make the shell, two molds were constructed, one for the back half and one for the front half (Figure 21). These molds were created in the rapid prototyping FDM machine. They were then covered in epoxy resin and then sanded to get a smooth inside finish. Wax and a spray-on lubricant were applied to the molds as a release agent. Two layers of carbon fiber and Kevlar hybrid fabric were laid on top of each other at alternating orientations, letting the first set before the second was applied. A vacuum pump device and airtight bag were used to make sure the fabric conformed to the mold. After fully drying, they were machined to mount on the RVP pan base. A SolidWorks model of both the molds and the shell can be found below.

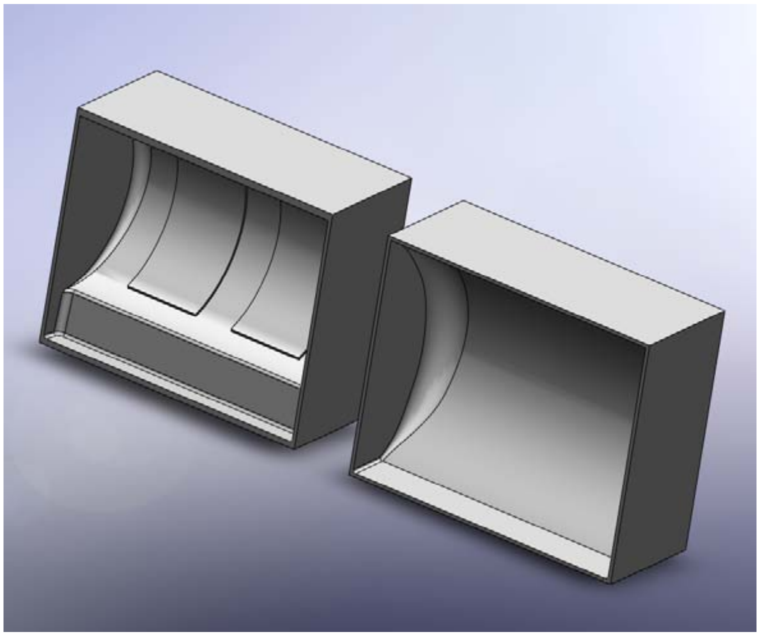


Figure 21. SolidWorks Model of Shell Molds

3D Vision Design

Once the Z800 3D vision goggles were received, they were tested on a lab computer. The lab computers do not have the recommended *Nvidia* video cards that are natively compatible with the goggles. See Appendix VI for a list of all the relevant computer components and options. After consulting with the goggle retailers, it was decided to try using them with the current *ATI* card and special drivers from monitor maker *iZ3D*. After trying many settings, a demo screen in the driver had the appearance of trying to display in 3D, but there was noticeable flickering and horizontal scan lines that detracted from the effect. A short time later the computer crashed and stopped recognizing the goggles; this problem could not be resolved in the lab.

Over Thanksgiving break, a team member tested the goggles on his home computer using a recommended *Nvidia* GeForce 6800 card. Using 91.31 forceware and stereo drivers allowed easy use of 3D mode. The driver demo worked flawlessly, and 2 games worked with varying 3D effect. The stereoscopic player from *3dtv* was also installed and used to watch numerous demo movies with good effect and no problems.

Because of the problems experienced trying to get the *ATI* video cards in the lab to work with the goggles and the demonstrated success of an Nvidia card, the team procured two *Nvidia* 6800 video cards to install and use. This simplified the process greatly and allowed the team to consult the goggle manufacturers for support. Additionally, the *3dtv* Stereoscopic player also natively supports the *Nvidia* output. This software and the related Multiplexer software from *3dtv* was focused on as the methodused to capture, transform, and output the video signals so that they can be displayed by the goggles in real time.

Statement of Analysis of Motor Specification

Problem Statement

The task of finding a motor proved to be very difficult. The motor needed to be able to move the vision platform quickly while not adding much weight to the design. The motor also needed to be reversible. Preferably, the motor was to be connected to an encoder and would not be backdriveable. Finding a motor and gearhead combination that achieved the desired torque and speed with minimal backlash was especially difficult for the range of size and weight. The specifications indicate that the entire head needs to weigh less than 4 pounds and fit inside an 8"x8"x10" box. Additionally, the head needed to be able to move with an angular acceleration of 1800 deg/s^2 in both directions.

Assumptions

A variety of assumptions were made in the calculations to analyze the motor. The exact weights of the final components were estimated because the design was being refined during the motor selection process. Also, the helmet that will be used to protect the head was not completely designed, thus it was approximated as a thin sphere with a radius of 4 inches and a weight of one pound. The screws, shoulder bolts, camera lenses, hub, wires and other forms of attachment did not have weight information available and thus were approximated. The specification of the lenses can be found in Appendix VII.

Analysis:

The motor torque was the key feature in selecting a motor. The torque was calculated as the product of the angular acceleration and the mass moment of inertia (Equation 1).

$$\tau = I\alpha \qquad [1]$$

where:
τ is the torque [N-m]
I is the mass moment of inertia [kg-m]
α is the angular acceleration [rad/s^2]

The parameters for the motor calculations were taken from the specifications (Table 4). By appropriately placing coordinate systems in the assembly of the head, the mass moments of inertia were calculated by SolidWorks (Table 5).

Table 4. Parameters for motor calculations

Parameters		
Min. Ang. Acceleration	1800	deg/s^2
Min. Ang. Acceleration	31.41	rad/s^2
Min. Ang. Speed	200	rpm
Min. FS	2	

Because the helmet was being designed in parallel, the exact moment of inertia was unknown. The helmet was assumed to be a thin sphere with a radius of 4 inches, so as to enclose all the major pieces of the platform (Equations 2).

$$I = \frac{2}{3}mr^2 \qquad [2]$$

where:
I is the mass moment of inertia [kg-m]
m is the mass [kg]
r is the radius of the sphere [m]

This moment of inertia value was included as a rough estimate in the design calculations.

Table 5. Moments of inertia for Pan and Tilt

Mass Moment of Inertia				
	Mass (lb)	**Mass (g)**	**Pan Moment ($g\text{-}mm^2$)**	**Tilt Moment ($g\text{-}mm^2$)**
Bumblebee2	0.75	343.0	7.82E+05	1.66E+05
Firefly (x2)	0.17	75.2	1.42E+05	1.42E+05
Upper Pulley (Tilt)	0.01	4.5	2.95E+05	3.41E+03
Lower Pulley (Tilt)	0.01	4.5	2.65E+05	--
Tilt Shaft	0.02	8.5	7.10E+04	5.83E+01
Tilt Bracket	0.16	74.1	2.46E+05	2.38E+04
Bearing	0.00	0.8	7.12E+03	1.43E+01
Shoulder bolt	0.01	6.2	6.39E+04	4.74E+01
Pan Assembly	0.47	213.0	1.34E+06	--
Motor mount	0.07	30.7	4.59E+04	--
Motor	0.24	111.0	4.43E+04	--
Helmet*	1.00	454.5	3.13E+06	3.13E+06
Gearhead	0.24	111.0	3.51E+05	--
Pan Pulley	0.09	40.7	3.32E+03	--
Pan Motor Pulley	0.09	40.7	1.44E+05	--
				--
Total Excel	3.34	1518.6	6.93E+06	3.46E+06

The final values of the moment of inertia were roughly 6,930,000 $g\text{-}mm^2$ in the pan direction and 3,460,000 $g\text{-}mm^2$ in the tilt.

Final Answer

Once the moments of inertia were summed together, the final torque values were tabulated (Table 6). The tilt motor was found to require roughly 109 mNm of torque while the torque necessary to move the RVP in the pan direction was about 218 mNm.

Table 6. Final torque values

	Req'd Torque (mNm)	Motor Torque (mNm)	FS
Pan	217.82	800	3.67
Tilt	108.82	800	7.35

Due to the size constraints, the motor required needed to be extremely small. Also, since the motor had to move quickly and in both directions, a DC motor was chosen. A motor was specified from MircoMo, one of few companies that manufactured extremely small, yet powerful, motors. The chosen motor was specified to achieve 16 mNm at normal operating conditions. Additionally, an optical encoder was placed directly on the back. To increase the torque, a harmonic gearhead was chosen. This gearhead was chosen because it almost completely eliminates backlash while increasing the torque. With a gear ratio of 50 this combination is capable of running at 800 mNm. This motor and gearhead combination provided a factor of safety of 3.67 for the pan mechanism and 7.35 for the tilt mechanism. Both of these values were well above the specified factor of safety of at least 2.

The motors could achieve the torque but they also needed to be able to move quickly. The maximum angular acceleration of the motor was specified at 140,000 rad/s^2. With the gear ratio specified, this is about 160,000 deg/s^2. Additionally, a minimum speed of 200 rpm was required. This specification, however, was not met. The no load speed of the motor was 8100 rpm but with the gear ratio, this is reduced to only 162 rpm. Initially this was a concern but after building the platform the speed of the head is sufficient. In fact, a speed much faster than the current motion would likely cause discomfort to the operator looking through the cameras.

Tiny motors were necessary because of size and weight constraints. The larger concern was that the large gear ratio would completely negate the speed and acceleration of the motor. The reason that the Micromotor was chosen was because it would be able to achieve the necessary torque and still keep the acceleration high enough.

Statement of Significance

The calculation of the torque was of great significance to this project. This calculation required the collaboration among almost all of the specifications listed. Once the required torque was calculated, it was a matter of finding appropriate motors that were also compatible with zero backlash gearheads, as well as encoders.

Component Selection

Two major components were selected in the design of the RVP. The combination of the motor, encoder and gearhead was essential to satisfy the speed, acceleration, and accuracy of positioning constraints. Additionally, the timing belt selection was also vital in achieving these specifications.

The motors were Series 2342-S0-12-CR from MicroMo with optical encoders OPEC07 attached on the back. These encoders are indexing encoders that determine the position of the motor relative to an initial home. There was one low-backlash gearhead attached to the shaft of each motor. These were harmonic gearheads Series CSF-08-50-2XH-F from Harmonic Drives LLC. The gearheads had 2 arc-min of backlash, or the equivalent of $1/30^{th}$ of a degree, which was well below the previously specified 1 degree. The gearhead had a 50:1 gear ratio that was used to achieve the appropriate torque. The calculations and requirements for torque were discussed in depth in the Statement of Analysis of Motor Specification. The motor output shaft mates with a receiver of matching size on the gearhead, and is secured with 2 set screws. A special connecting plate between the motor and gearhead hold the two pieces together and attach the powertrain to the head. The mounts for both motors are slotted to allow for proper tensioning of the timing belts. There is a flanged output on the gearhead so a special shaft will need to be machined to connect the gearheads to the pulleys. The same motor-gearhead-pullley combination is used for both pan and tilt to simplify the design, controls and machining.The motion of the head was specified to achieve 200 rpm and 1800 deg/s^2. The DC motor that was specified has a no–load speed of 8500 rpm. After the gearbox this speed was reduced to 283 rpm, which is still above the specified 200 rpm. In the motor calculations an acceleration of 1800 deg/s^2 was used to determine motor torques to ensure that the accelerations would be adequate. The motor was specified based on these calculations, thus should be able to achieve 1800 deg/s^2. The calculations for these numbers are shown in more detail in the Statement of Analysis of Motor Specification section of this report.

GT2 belts were chosen to transmit the power from the motor to the robot head. This type of timing belt was specified because they were specifically designed to minimize backlash and increase accuracy. These belts have less backlash than typical GT and HTD belts (Figure 22).

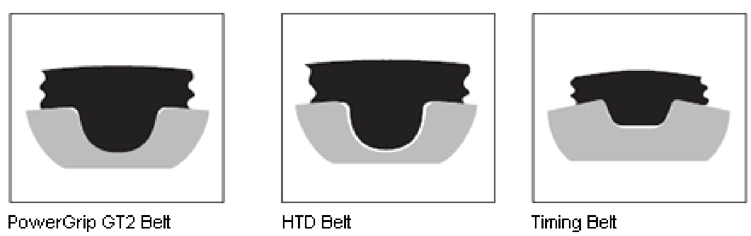


Figure 22. Comparison of belt profiles (from Gates Corporation)

These belts were chosen because they are typically very thin but strong. A 6 mm belt width with a 1.003" diameter pulley should be more than satisfactory for this application. This decision was based on the strength of the belt. In depth calculations can be found in the Safety section.

The cameras were specified to be able to have a very accurate resolution of .01° The field of vision (FOV) is a function of the focal length of the two cameras. The FOV is a fixed value on the Bumblebee2 of 97°. The focal length of the Firefly MVs is dependent on the lenses. The lenses that are specified can only achieved a 43.7° FOV.

In accordance with the specifications, the final design was a 2 DOF gimbal that has 180 range of motion in the pan and 135 in the tilt. The Bumblebee2 and two Firefly MVs are implemented in the design. Because the Bumblebee2 is a binocular camera, the total number of cameras was 4. The Bumblebee2 has a frame rate of 48 fps and a maximum resolution of 648 x 488. The Firefly MVs are able to realize 61 fps at a maximum resolution of 752 x 480.

Budget and Bill of Materials

This project received a sizeable grant for naval research. Because of this, achieving the above specifications and in a timely fashion were valued more than cost. Despite high prices, the necessary equipment to explore 3D vision and ensure minimal backlash were able to be purchased. Also, extra stock material, additional belt sizes and bearings were purchased as a precaution (Figure 23, Figure 24, Figure 25, Figure 26). An estimate of approximately $10,000 was spent on the project, including the cameras and the operating system for the RVP.

		Part #	Purchase Description	Company	Material	Unit Type/Size	Unit Price	Amt	Price
1	PC104	MM-32DX-AT	PC104 Board	Diamond Systems		Individual	$0	1	$0.00
2		HE104+DX 108	PC104 Board - Power Supply	Tri-M		Individual	$299	1	$299.00
3		ETC-NANO-104	PC104 Board - Basebaord	ACCES I/O		Individual	$229	1	$229.00
4		CAB-ETX-ATX	PC104 Board - Power cable	ACCES I/O		Individual	$20	1	$20.00
5		ETX-PM1.4G	PC104 Board - 1.4 Ghz CPU	ACCES I/O		Individual	$749	1	$749.00
6		ETX-LFHSPWFAN	PC104 Board - Heat Spreader with Cooling Fan	ACCES I/O		Individual	$26	1	$26.00
7		CPF-8GB-I1	PC104 Board - 8GB Flash	ACCES I/O		Individual	$219	1	$219.00
8		SODIMM-1GB	PC104 Board - Memory Module 1 GB	ACCES I/O		Individual	$99	1	$99.00
9		MAG05-0300S050	PC104 Board - Mag 3.5	MEMSense		Individual	$669	1	$669.00
10		AIB	PC104 Board - Analog Interface	MEMSense		Individual	$110	1	$110.00
11	Carbon Fiber	FG-CF5549	Carbon Fiber Fabric	U.S. Composites		Yard	$27	1	$26.50
12		FG-CF5702	Carbon Fiber Fabric	U.S. Composites		Yard	$5	2	$10.00
13		FG-CK99150	Blue Carbon/Kevlar Hybrid Fabric	U.S. Composites		Yard	$39	1	$38.50
14		FG-CK99450	Orange Carbon/Kevlar Hybrid Fabric-	U.S. Composites		Yard	$39	1	$38.50
15		EPOX-635312	635 Thin Epoxy Resin System, Quart+10oz	U.S. Composites		Quart	$21	1	$20.75
16		EPX-P11	Resin Pumps, 1-1 Ratio	U.S. Composites		Set of 2	$6	1	$6.25
17		VB-P56150	Peel Ply Release Fabric, 60" wide	U.S. Composites		Yard	$6	1	$5.50
18		PD-E16	Epoxy Parfilm Mold Release Spray	U.S. Composites		Can	$13	1	$12.95
19		KLY-01	Klean Klay	U.S. Composites		Lb	$3	2	$5.00
20		REX-224	Partall #2 Paste Wax	U.S. Composites		24 tub	$10	1	$9.75
21		SQ-04PK	4" wide Squeeges/Spreaders	U.S. Composites		Pack 25	$10	1	$10.00
22		SHR-KV023	3" Blade Kevlar Shears	U.S. Composites			$28	1	$27.50
23		GLV-TD050	Tongue Depressor Mixer Sticks	U.S. Composites		Pack 50	$2	1	$2.25
24		GLV-LL100	Disposable Latex Exam Gloves	U.S. Composites		Pack 50	$10	1	$10.00
25		VB-BLE060	Bleeder/Breather Cloth	U.S. Composites		Yd	$4	1	$4.00
26		VB-BT25	Sealant Tape	U.S. Composites		25ft roll	$7	1	$6.95
27		VB-VF02110	Nylon Baggin Film	U.S. Composites		Yd	$4	3	$12.75

Figure 23. BOM Part 1

		Part #	Purchase Description	Company	Material	Unit Type/Size	Unit Price	Amt	Price
28	Electronic Systems	PA3	Super High Gain Micro Audio System	Super Circuits		Wired Mic	$10	2	$19.98
29		V-2240-BF45	1.8" Miniature Speaker -Visaton BF45-4ohm	Soundlabs Group		Speaker	$17	1	$17.39
30		V-2909-K28WP	1.1" Miniature Waterproof Speaker	Soundlabs Group		Speaker	$7	1	$6.62
31		Z800	3D Visor Z800	eMagin		Goggle Set	$1,314	1	$1,314.00
32		FFMV-03M2M/C	Firefly MVFFMV-03M2M/C	Point Grey		Individual	$200	2	$400.00
33		B2-03S2	Bumblebee 2	Point Grey		Individual	$2,000	1	$2,000.00
34		2036	Unibrain Fire-I Digital Camera	Unibrain		Individual	$109	2	$218.00
35		FFWB-HUB-5PORT	Firewire Hub	Point Grey		Individual	$139	1	$139.00
36		NT57-909	6.4mm FL, High Res. Video lens	EdmundOptics		Individual	$39	2	$78.00
37		NT57-909	C-Mount to µ-Video Lens Adapter w/Oring	EdmundOptics		Individual	$25	2	$50.00
38		NT64-102	M12 Lock Nut for Micro-Video Lenses	EdmundOptics		Individual	$8	2	$15.00
39		B00030GSJY	Joystick - Saitek X52 Flight Control System	Amazon		Individual	$90	1	$89.98
40		RR-9S6FP-12G	Firewire 800 Extension Cable 12 inches	USB Firewire		Individual	$17	1	$16.95
41		RR-9S6FP-24G	Firewire 800 Extension Cable 24 inches	USB Firewire		Individual	$19	1	$18.95
42		RR-9S6S-06G	Firewire 800/400 Cable 9/6, 6 inches	USB Firewire		Individual	$18	3	$52.50
43		RR-9S6S-12G	Firewire 800/400 Cable 9/6, 12 inches	USB Firewire		Individual	$18	2	$35.30
44		NT54-629	C-Mount 10mm	EdmundOptics		Individual	$18	2	$36.00
45		828-OPB931W51Z	Photo-interrupter Sensor	Photointerrupter Sensor		Individual	$5	3	$15.93
46	Motors and Gearheads	512-VC-	Coreless DC Motor/Optical Encoder	MicroMo		Individual	$198	3	$594.90
47		CA-316701	Encoder Cable	MicroMo		Individual	$8	3	$22.50
48		CSF-08-50-2XH-F	Harmonic Gearhead (GR 50, Size 8 model CSF-2XH)	Harmonic Drives LLC		Individual	$600	2	$1,200.00
49	Shafts	5227T13	Carbon Steel Rod 5/32" Diameter	McMaster-Carr		Individual	$14	1	$14.13
50		1257k114	Rotary Motion Shaft 1/4" OD	McMaster-Carr		Individual	$14	1	$14.13
51		5227T11	Carbon Steel rod 3/32", 6" length 12L14 Carbon Steel	McMaster-Carr		Individual	$4	1	$3.84

Figure 24. BOM Part 2

		Part #	Purchase Description	Company	Material	Unit Type/Size	Unit Price	Amt	Price
52	Stock Material	8364T18	Stainless Steel - Pan Shaft	McMaster-Carr	Stainless Steel	Individual	$4	1	$3.84
53		6061K411	Stainless Steel - Tilt Shaft	McMaster-Carr	Stainless Steel	Individual	$4	1	$3.84
54		897K492	Aluminum 6061 - Tilt Bracket	McMaster-Carr	AL - 6061	Individual	$4	1	$3.84
55		897K417	Aluminum 6061 - Motor Mounts and Pan Bracket	McMaster-Carr	AL - 6061	Individual	$4	1	$3.84
56		897K329	Aluminum 6061 - Base Plate, 2 Pan Brack Arms	McMaster-Carr	AL - 6061	Individual	$4	1	$3.84
57		9008K481	Aluminum 6061 - Shaft Support	McMaster-Carr	AL - 6061	Individual	$4	1	$3.92
58		89155K971	Aluminum 6061 - Base Struts	McMaster-Carr	AL - 6061	Individual	$2	1	$2.44
59		8975K562	Aluminum 6061 - Firewire Bracket	McMaster-Carr	AL - 6061	Individual	$4	1	$3.92
60	Pulleys	A 6D51-040DF0608	Timing Pulley, GT2 2mm Pitch, Pitch Dia 1.003" w Fairloc hub	SDP-SI		Pulley	$65	3	$195.00
61		A 6A51-048DF0608	Timing Pulley, GT2 2mm Pitch, Pitch Dia 1.003" w hub	SDP-SI		Pulley	$8	3	$22.80
62		A 6R51M107060	107 Groove Timing Belt, GT2 2mm Pitch, 6mm Wide	SDP-SI		Belt	$5	2	$10.38
63		A 6R51M108060	108 Groove Timing Belt, GT2 2mm Pitch, 6mm Wide	SDP-SI		Belt	$9	2	$18.22
64		A 6R51M110060	110 Groove Timing Belt, GT2 2mm Pitch, 6mm Wide	SDP-SI		Belt	$4	2	$7.20
65		A 6R51M112060	112 Groove Timing Belt, GT2 2mm Pitch, 6mm Wide	SDP-SI		Belt	$5	2	$10.48
66		A 6R51M114060	114 Groove Timing Belt, GT2 2mm Pitch, 6mm Wide	SDP-SI		Belt	$6	4	$22.76
67		A 6R51M115060	115 Groove Timing Belt, GT2 2mm Pitch, 6mm Wide	SDP-SI		Belt	$3	2	$5.10
68		A 6R51M116060	116 Groove Timing Belt, GT2 2mm Pitch, 6mm Wide	SDP-SI		Belt	$6	2	$12.18
69		A 6R51M118060	118 Groove Timing Belt, GT2 2mm Pitch, 6mm Wide	SDP-SI		Belt	$4	4	$14.96
70		A 6R51M120060	120 Groove Timing Belt, GT2 2mm Pitch, 6mm Wide	SDP-SI		Belt	$8	2	$16.50

Figure 25. BOM Part 3

		Part #	Purchase Description	Company	Material	Unit Type/Size	Unit Price	Amt	Price
71		SSMERI-541	Angular Contact Torque Tube Bearing (Thrust bearing)	Alpine Bearing		Individual	$1	4	$3.96
72		57155K322	Ball Bearing, 1/4" Shaft Diameter	McMaster-Carr		Individual	$4	6	$21.84
73		6384K354	Ball Bearing, 3/8" Shaft Diameter	McMaster-Carr		Individual	$2	2	$3.62
74		98410A113	Retaining Rings - External, Snap, 1/4"	McMaster-Carr		100 Pack	$5	1	$5.24
75		92010A118	M3 8mm Flathead Machine Screws, 18-8 Stainless Steel	McMaster-Carr		100 Pack	$7	1	$6.75
76		91801A111	M2 10mm Flathead Machine Screws, 316 SS	McMaster-Carr		25 Pack	$5	2	$9.70
77		93996A847	Shoulder Screw - 1/4" Shoulder Diameter	McMaster-Carr		Individual	$6	1	$5.68
78		98804A006	Stainless Steel Threaded Rod- 24" 5-40	McMaster-Carr		Individual	$9	2	$18.74
79		93615A405	Screw - 18-8 SS Head Sckt Cap 1/4"-20, 3/8" length	McMaster-Carr		Pack of 10	$4	1	$4.18
80		94035A569	18-8 SS Precision Hedx Socket Shoulder Screw, 1/4" diam, 1/2" l, 10-24	McMaster-Carr		Individual	$6	2	$12.78
81		90259A124	Thin Wall Insert, 10-24 int thread	McMaster-Carr		Pack	$3	1	$2.79
82		90592A004	Hex Nut, Class 6 M2, .4 mm pitch, 1.6 mmm h	McMaster-Carr		Pack	$6	1	$6.25
83		90695A025	hex nut, m2, .4 mm pitch, 1.2 mm h	McMaster-Carr		Pack	$4	1	$4.34
84		91113A007	Lock washer, no. 6 screw size, 3" OD, .01-.01" thick	McMaster-Carr		Pack	$6	1	$5.93
85		91801A111	316 SS flat head Phil machine screw, M2, 10 mm lenggth	McMaster-Carr		Pack	$8	1	$7.76
86	Bearings and Screws and Stock Material	92010A006	18-8 SS flat head phil machine screw, m2 size, 12 mm length	McMaster-Carr		Pack	$5	1	$4.73
87		91290A120	12.9 socket head cap screw, alloy steel, m3 thread, 5/8"	McMaster-Carr		Pack	$10	1	$9.92
88		92210A150	18-8 SS flat head sckt cap screw, 6-32, 5/8" length	McMaster-Carr		Pack	$1	1	$0.64
89		90255A152	alloy steel button head socket cap screw, 6-32, 7/8"	McMaster-Carr		Pack	$3	1	$3.24
90		91255A081	alloy steel button head socket cap screw, 2-56, 1/2" length	McMaster-Carr		Pack	$4	1	$3.84
91		92949A114	18-8 ss button head socket cap screw, 4-40, 7/8" length	McMaster-Carr		Pack	$14	1	$13.79
92		94831A001	serrated-flange hex locknut, 6-32, 5/16" width, 11/64" o'all height	McMaster-Carr		Pack	$6	1	$5.59
93		93501A007	serrated belleville washer, no. 6 M3.5 screw size, 24" OD, .02 " thick	McMaster-Carr		Pack	$6	1	$6.46
94		26309-ND	Hex Screw Driver .9mm .035"	DigiKey		Individual	$4	1	$3.55
95		27507-ND	Hex Screw Driver .7mm .027"	DigiKey		Individual	$5	1	$4.65
96		8586K162	Plastic ABS 12x12x1/8"	McMaster-Carr		Individual	$68	1	$68.18
97		91099A167	4/40 - 1/2" Flathead Screw	McMaster-Carr		Pack of 100	$4	1	$4.15
98		91794A117	4-40 Fillister head, 18-8 SS Screw 1-1/4"	McMaster-Carr		Individual	$14	1	$13.65
99		1556A51	Screw	McMaster-Carr		Individual	$24	1	$24.48
100		8560K171	Clear Cast Acrylic Sheet .060" Thick, 12" X 12"	McMaster-Carr		Individual	$19	1	$18.61
101		8574K24	Polycarbonate Sheet 1/16" Thick, 12" X 12", Clear	McMaster-Carr		Individual	$21	1	$20.80
102		8975K413	3/8" Aluminum Plate	McMaster-Carr		Individual	$33	1	$32.80
103		26955A25	HSS Hand Tap Plug, 5-40, 2 Flute	McMaster-Carr		Individual	$20	1	$19.79

Figure 26. BOM Part 4

Discussion

During the process of fabrication, various changes were made to the design. Electrical components were much larger than expected and not enough space was allocated for electrical equipment. Additionally, the pan mechanism was changed to accommodate the wires and prevent them from twisting. Finally, new cameras were purchased after difficulties with Point Grey cameras and software.

Motor/Gearhead Connector

When the gearheads arrived in the lab, it was found that the dimensions shown online were not entirely accurate. There was an extra protrusion along the flange that did not allow the original motor-to-gearhead connector to fit properly. The connection piece was made larger to accommodate the extra protrusion and allow the motor and gearhead to screw in properly.

Tilt Shaft Connection

Originally, the tilt shaft was to be press-fit into the tilt bracket. Later it was determined that friction would be insufficient to keep the shaft from slipping against the bracket. Instead, the bracket was slotted with a screw hole going through the slot. The shaft fit into the hole in the bracket and a screw was used to tighten the bracket and clamp it around the shaft.

Electronic Implementation

As with any design project, modifications were made before fabrication. Specifically, the pan mechanism changed significantly from the previous design. Additionally, it was decided to add a hard stop, as well as an optical sensor to protect the motors and gearheads, should a bug in the programming occur. Furthermore, major changes in the base plate were made to accommodate the pan mechanism change, as well as to provide space for three new circuit boards.

Electrical Connections

The electronics involved in this Robotic Vision Platform were very complex. The diagram below illustrates how the components were connected (Figure 27).

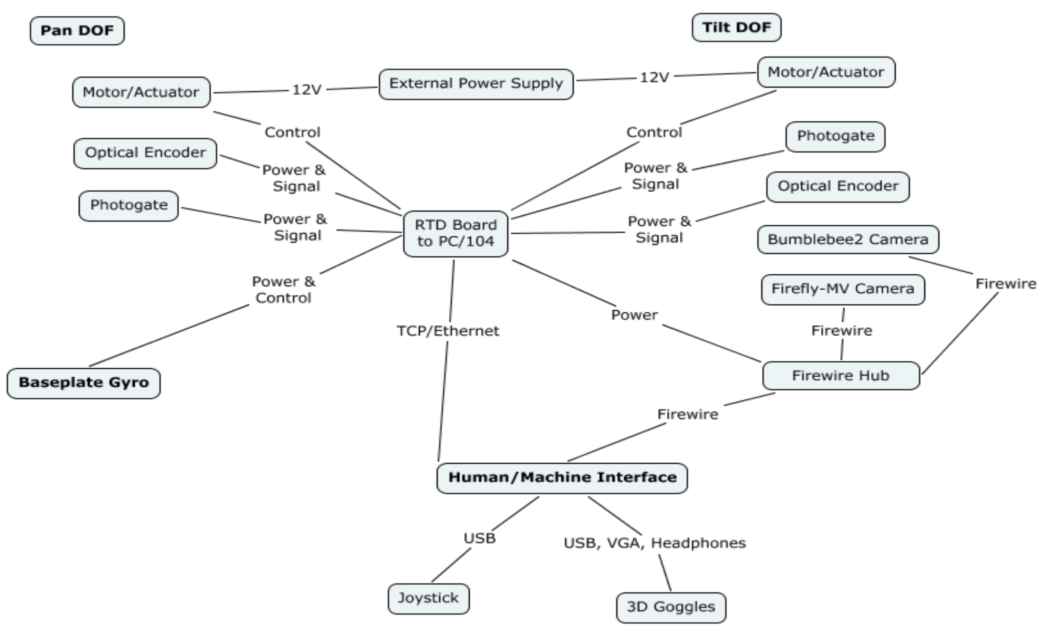


Figure 27. Electronic Connection Diagram

Most of the electrical equipment ran through the PC/104 board and were then routed to the human/machine interface. The sensors on the tilt and the pan bracket, as well as the base plate, needed to be connected to the PC/104 to power the sensor as well as send a signal to the computer. The motors were controlled via the PC/104 and received power externally. The PC/104 was connected to the Human/Machine Interface via an Ethernet cable. The cameras will be connected to a FireWire hub to simplify the number of cables that will be twisting around the head, but these will run back to a Windows PC for the visual Human/Machine Interface. Currently, 2 separate Windows PC's are used for the video and Yobotics/joystick control, although the team will attempt to consolidate this to one computer for the Expo and future operations. A wiring diagram can be found in Appendix IX.

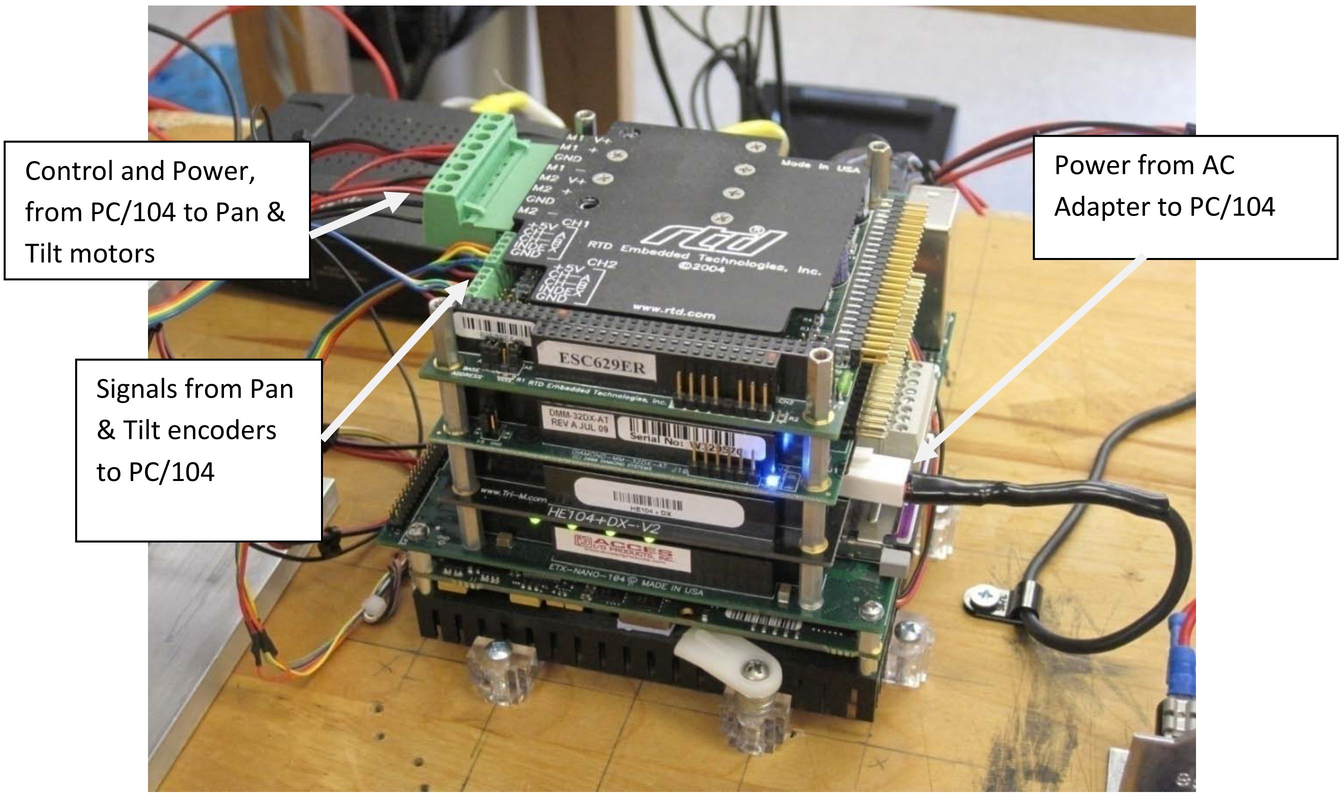


Figure 28. Connections to PC/104

Pan Mechanism

The main reason for the change was to accommodate for the wires coming from the tilt motor, cameras, and sensors above the pan base. There was a major concern that the wires might twist around the pan base, the pan belt, parts of the old pan mechanism, or even around themselves and thus snap at their connections. The new design has a ¾ inch hole through the axis of rotation; the wires will be fed through this hole and down through the base plate to the PC/104. The chance of twisting around parts and possibly breaking at their connections has been significantly lessened by the new design (Figure 29).

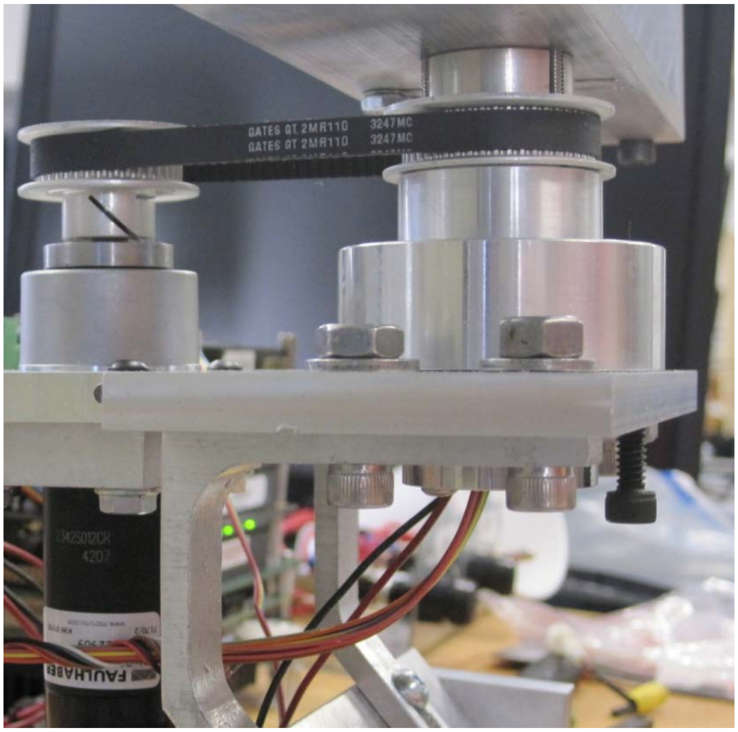


Figure 29. Fabricated Pan Mechanism

In addition to dealing with the wires, the new pan mechanism had more structural integrity and had fewer moving parts. The new design rotated around two angular bearings, whereas the prior design used two regular ball bearings and a thrust bearing (Figure 30).

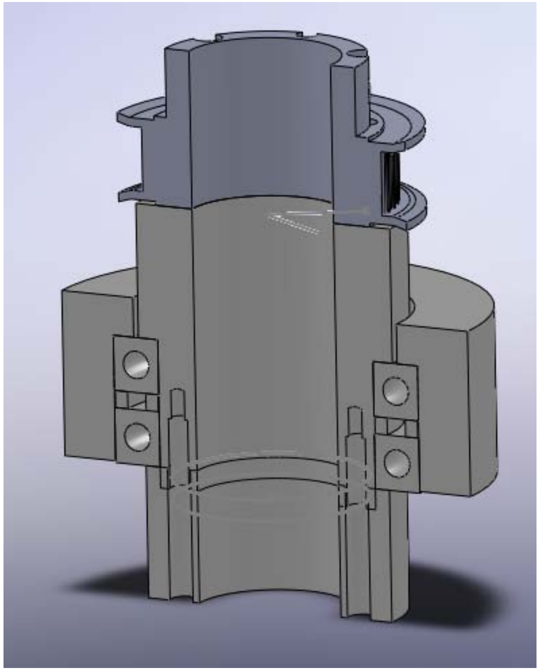


Figure 30. New Pan Mechanism

Previously, the bearings were exposed and all the force from the head was placed on the shaft. If turned upside down, all the force would be placed on one simple retaining ring. Also, the shaft was complex part to machine. The new design incorporated the use of angular contact bearings, which can take both radial and axial loads when preloaded correctly, which eliminated the need for both thrust and ball bearings. The inner and outer shells are used for support and are also used to correctly preload the angular contact bearings. The main drawback is the tight tolerances required to correctly preload the angular contact bearings.

Hard Stop and Sensor

A hard stop and a photogate sensor were implemented into the design. In the event that both the program and the sensor cannot stop the motors from turning uncontrollably, a hard stop was added to avoid the destruction of the expensive equipment that is on this RVP. This consisted of a screw that is placed at the ends of the range of motion for both the pan and tilt axes. This screw physically prevents the RVP from rotating further than intended.

A photogate sensor was originally planned to be placed at the zero location for the pan and the tilt mechanism, or when the head is facing straight forward. This was to be used as a safety measure to double check the position of the bracket, in conjunction with the optical encoder on the back of the motor. If the sensor gets to a certain position, it will disrupt the program or shut off the power. This, however, was not implemented. The RVP was becoming cluttered after all the FireWire cables from the cameras, the circuit boards and other wires were attached. There was limited space on both brackets to place sensors. Instead of implementing this idea, just a hard stop was added.

Base Plate

The base plate was modified to fit three circuit boards, 2 x 3 inches in size (Figure 31). These hold the gyro, power safety fuses, and other electronic signal connections and converters. The boards could not be placed underneath the plate, near the motor, because the electrical signals could be altered by the magnet in the motor.

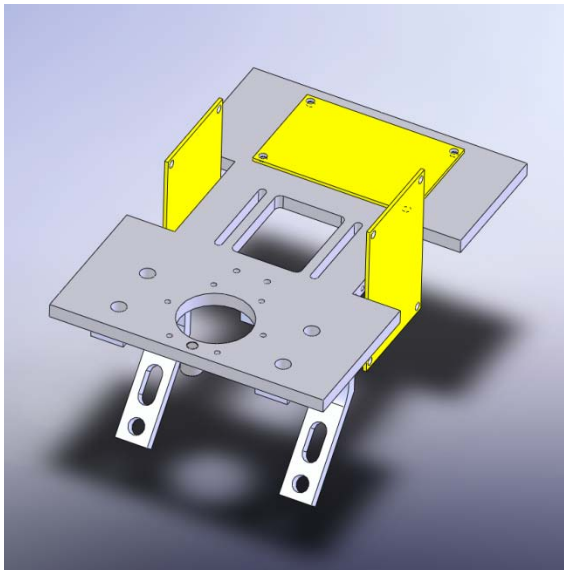


Figure 31. New Base Plate

The plate was redesigned to have two pockets where circuit boards were placed vertically. This allows for a more versatile arrangement of the board and easier access to the wires exiting the bottom of the pan mechanism. The base plate was also extended in the back to accommodate the third and final circuit board holding the gyro. The area under the plate in the back was not used because it was believed things placed here would hit the PC/104 and RTD board when placed on the actual biped body. Extra room along the sides should be sufficient to accommodate quick-disconnect adapters for wires.

FireWire Hub

Originally it was planned to place a hub on the tilt bracket to collect all the Firewires cables from the three cameras and produce one output wire. This would minimize the number of wires going through the pan mechanism and make the wiring much simpler. However, difficulty arose because the hub limited the data rate through each connection to just 100 Mbps (instead of 400). This was insufficient to run the Point Grey Firefly MV cameras any faster than 7.5 fps, and was deemed unacceptable. The specification was to have the cameras running at 30 fps.

The purchase of the Unibrain Fire-i cameras eliminated the need for the Firewire hub since each camera contained 2 FireWire ports, allowing the cameras to be daisy-chained so just 1 cable to the computer was needed for the 2 cameras.

Camera Choices

Setting up the vision system turned out to be one of the most difficult parts of the project. The discovery of *3dtv's* Stereoscopic Multiplexer and Player appeared to be the perfect solution for the project goals. The system was designed to work with almost any webcam or digital video camera, and was used successfully on the lab computer using a set of Logitech USB webcams and a set of Panasonic digital camcorders connected through FireWire. With these, 3D live video was easily routed though the Multiplexer to the Player and goggles. Despite the simple, straightforward configuration used with these cameras, much of the semester was focused on getting the Firefly MV cameras to work with the Stereoscopic Multiplexer and Player.

Initial testing of the Firefly MV cameras simply involved making sure they worked in various combinations within the supplied Point Grey Research (PGR) Flycapture software. Not until the FireWire hub and special 6-to-9 pin 1394 cables arrived was the bandwidth problem discovered with the hub. After that, it was attempted to view the cameras in other programs, such as the Multiplexer and Player. However, the default PGR Software (Flycapture) and drivers tended to lock the cameras to PGR software, thus making them invisible as a camera to the computer and other programs. Instead of showing up as imaging devices in the Device Manager, they were “Point Grey Research Devices.” After working with PGR, this limitation was overcome by installing a new 2.0.3 version of the driver and making some registry changes (documented in the file “Registry Change with PGR Flycapture 2”). This allowed the computer and the Multiplexer to see PGR cameras, but only indicated that one at a time was present. If just one was connected, the Multiplexer would begin configuration and then fail because it wanted a second camera. If two PGR cameras were connected, configuration would not progress, presumable because it was trying to draw two feeds from the same “camera” instance.

PGR tech support suggested trying GraphEdit, part of a the extras pack in the February 2005 DirectX SDK, which allows users to manually choose audio and video devices and each step in the decoding and processing stream. Each step is called a filter, and hundreds of filter options are available depending on the hardware and software on the computer. Help making a graph can be found at http://www.3dtv.at/Products/Multiplexer/Installation_en.aspx#Recording. This and PGR support guided the production one of the more successful versions we used (Figure 32). This set-up also provided a way to simultaneously record and preview live video. This did allow two separate PGR cameras to be set up through the Multiplexer and was successful in recording a side-by-side file that could later be played back in 3D in the goggles through the Player. However, the live preview window displayed in GraphEdit did not display in a suitable format for 3D in the goggles. Additionally, trying to open the live Stereo Multiplexer feed in the Player resulted in errors suggesting that cameras were not connected, a format was not compatible, or the signal was not being carried through all the filters. Further efforts by PGR technicians were unable to resolve the problem, and determined it was likely a problem with their own DirectShow filters or drivers, and that they would work to resolve the issue in the future. It remains unclear if a custom graph is able to be carried back through the Stereo Player.

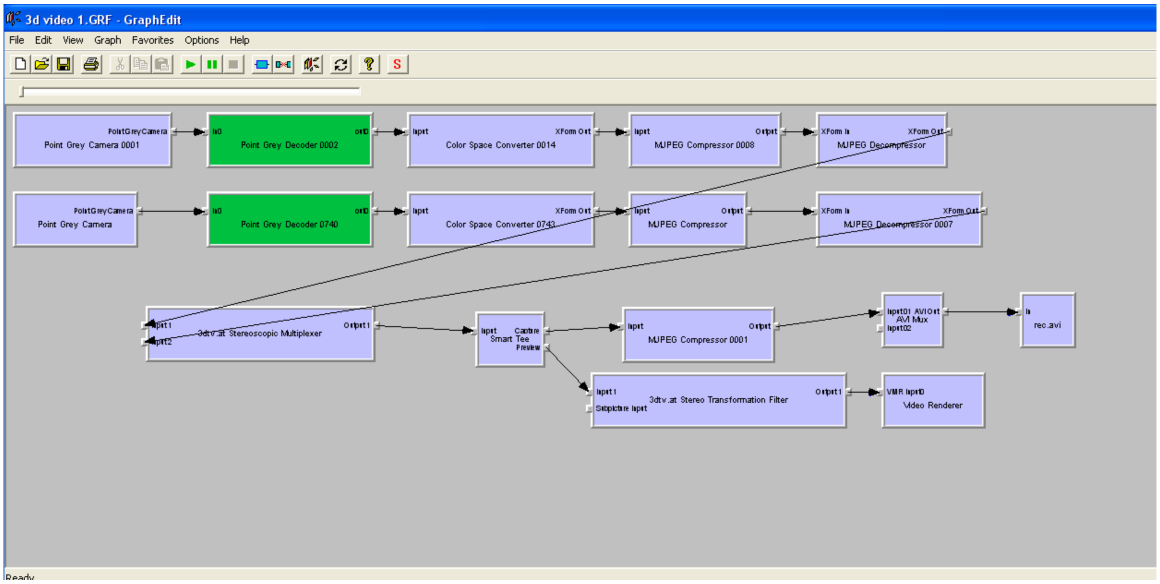


Figure 32. Attempted GraphEdit

After this, the Flycapture software was uninstalled and an alternate PGR package called Flystream was installed. After re-associating the Firefly MV cameras with this driver, the Multiplexer did begin to recognize separate instances of each camera when 2 or more were connected. As a result, the configuration did progress, even allowing for a live test preview of both cameras. However, after finishing the last step of the configuration wizard and trying to actually run the cameras through the multiplexer, the process failed and an error suggested the program could not connect to any (Point Grey) device. The same error appeared in the Player. Further research suggested that the root of the problem lied with the incompatible formats that the Firefly MV output (Y8, Y16, 8&16 bit raw) and that the Multiplexer accepted (YUV 4:2:2, RGB24&32). It seemed this problem could be addressed in GraphEdit and in preview screens, but could not be handled in the Multiplexer in a way that allowed for live 3D output to the goggles. The only near-term foreseeable option was to find new cameras that output a format supported by the Multiplexer.

Meanwhile, the Bumblebee2 stereo camera was largely ignored in the attempts to obtain 3D video in the goggles. Although specifications suggest the camera can output YUV4:2:2 and RGB formats, discussions with Point Grey indicated that the Bumblebee2 signal is in Byte Interleaved format, which alternates between left and right camera signals. A special program or code would need to be found or created to separate out the 2 cameras to use 3D vision in the current set-up. This was not achievable given team experience and time constraints. However, the Bumblebee2 is still present on the head and can be used with PGR Triclops software to give depth maps of the environment.

A new search for cameras showed hundreds of possible solutions, a list of which can be found at http://damien.douxchamps.net/ieee1394/cameras/ . The Unibrain Fire-i was selected from the list because it was inexpensive ($109), close to the same size as the Firefly MVs, had 2 FireWire ports, needed no additional lenses, included a matching photo screw mount, and was readily available. Most importantly, it clearly stated that it supported RGB24 and YUV 4:2:2 output, although at a less than ideal 15 fps. It may not be the best long-term solution, but was a good last minute substitute in late April.

Initial installation of the Unibrain cameras was tricky because the computer thought they were PGR devices and tried to assign them PGR drivers, even after all PGR software was uninstalled. The Unibrain software and drivers that were included on the CD could not install without hitting an error, but a newer version (Fire-i 3.80) downloaded from the Unibrain installed successfully. This installed a Fire-i application that allows a user to view and change the settings of all connected cameras, and associates the proper Unibrain Fire-i driver with the cameras. Two cameras independently connected to a single Firewire card show up properly in the multiplexer software and allow for a complete, successful setup. This carries through to the Stereo Player, which allows for live viewing of both streams in 3D in the goggles. Thus, everything works as advertised. The only complicated part is aligning the camera angles to create a similar image for each eye. The success from this setup suggests that the 2 cameras could also be daisy-chained together. For a full description of how to set up the cameras for 3D vision, see the user manual.

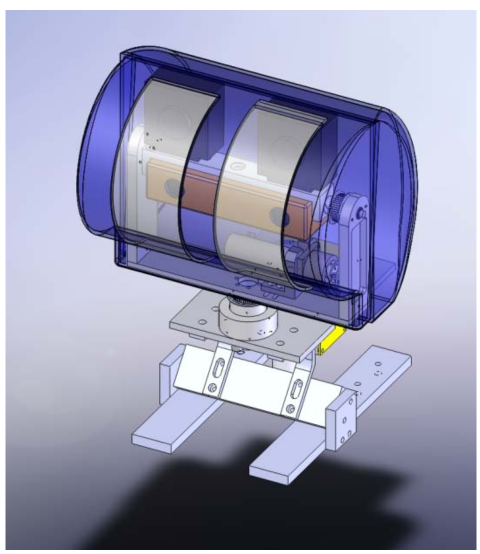


Figure 33. Final Design with Shell

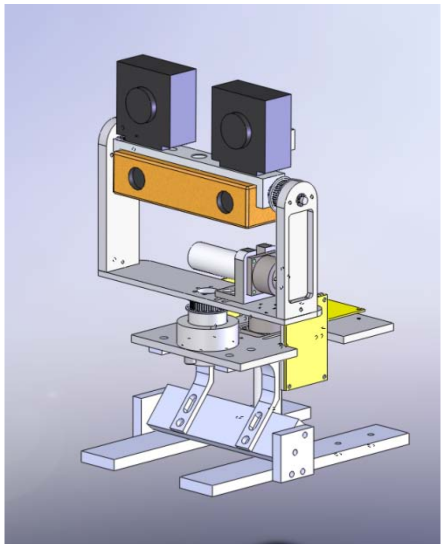


Figure 34. Final Design without Shell

Robotic Control System

The controls for the robotic vision platform are performed by an independently operating PC/104 computer. PC/104 is an embedded computer standard with a specific kind of connection that allows for a rugged stacking of boards (Figure 33). The computer used to control the RVP runs on the Solaris operating system. Solaris is a free, open-source Unix-based operating system. On the computer are a number of PC/104 boards.

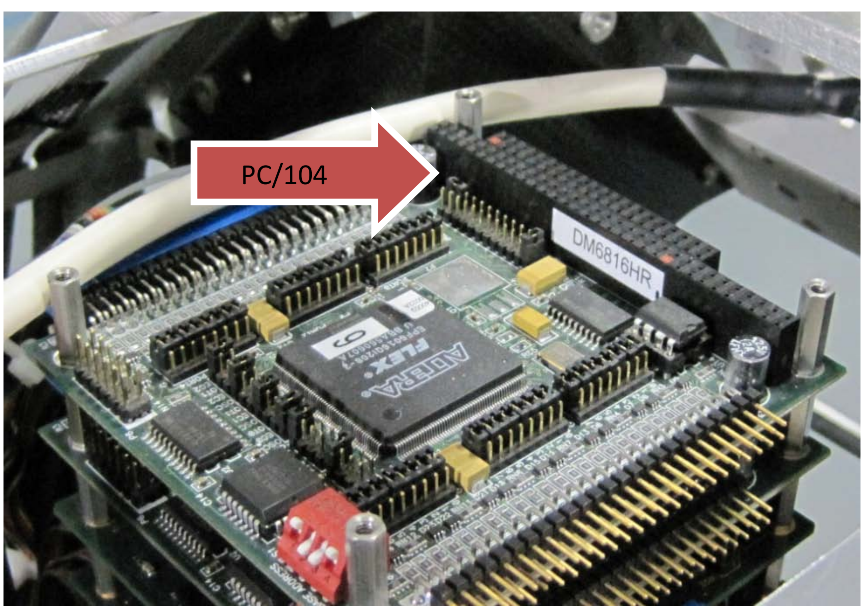


Figure 35. Top view of PC/104 stack showing PC/104 connection with white arrow

The PC/104 stack with a Solaris operating system was chosen because it duplicates the system used by the biped at IHMC. By using this stack, the controls can be tested at Bucknell or shipped to IHMC and tested there simply by replacing the motor control board from the top of the Bucknell PC/104 stack to that in the biped.

Solaris System Information:
Username: root
Password: robot
IP: 192.168.1.50
Host: 192.168.1.49

RTD Control Board

The PC/104 board that is used to control the DC brushed motors on the head is a Real Time Devices ESC629ER 2-channel DC servo motor controller board. The RTD board is capable of independently controlling two DC brushed motors as servo motors with encoders. Based on feedback from the encoders and using user-specified gains the controller is capable of controlling acceleration (current), velocity, or position of the motors. For the robotic vision platform there is a motor to control pan and another to control tilt connected to channels 1 and 2, respectively.

Motor power can be supplied by an on-board power supply on the RTD board (either +5 or +12 V) or by an external power supply. For the RVP, external power is used because the motors used in the RVP require more current than is available on the board and it is desirable to separate the power controller the motors and operation of the PC/104 stack. A standard DC power supply unit is set to 12V and connected to the “M1 V+” and “GND” screw terminals in order to provide the necessary power (Figure 34). These terminals are wired to the “M2 V+” and “GND” terminals for the second channel. The purpose of this external power supply is to provide “dirty” power to be sure that the draw from the motors does not interfere with the power to the encoders or the gyroscope. Motor wires are connected to the + and – terminals corresponding to the correct channel (M1 or M2)*.

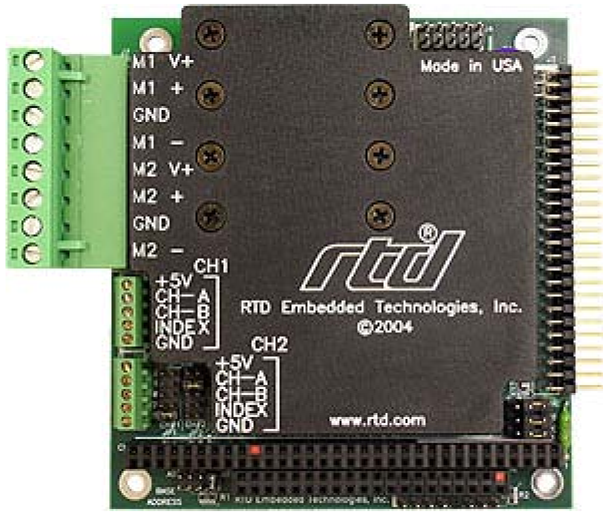


Figure 36. Top view of RTD ESC629ER control board displays screw terminals on left

For each motor channel there are five screw terminals corresponding to encoder power (+5V and GND), channels A and B (CH-A and CH-B) and INDEX. The encoders are power by an on-board 5V power supply (what is considered the "clean" power in the system).

Programming for the camera stabilization system was originally done in Java using Borland JBuilder 2006 software. This later version of the software was important to use because it is the same version used by IHMC (because of issues with some of the updates). However, this year IHMC switched to JBuilder 2008 and all appropriate changes were made to the code. There are few obvious changes except that it takes considerably longer to send the files from the host computer to the PC/104 computer.

Java is an object-oriented programming language created by Sun Microsystems. In Java, script can be organized using files called classes. A specific instance of a class is referred to as an object. This could be compared to the way that Bucknell is a university. Bucknell is a specific instance of the more general term university. Each class can contain any number of variables and methods. Methods are functions within a class that can perform a variety of tasks such as storing and retrieving variables. The method setPosition, for example, sends a signal to the ESC629ER board that sets the desired position to a specified angle. The following lines of code provide an example of how a class is created and a method can be called using the class ESC629ERAxisController.

```
ESC629ERAxisController panAxis = new ESC629ERAxisController(*)

// creates an object, panAxis, the * is where required

// information is fed into the constructer for the class such as
// axis number and name

panAxis.setDesiredPosition(newAngle)
```

```
// sets the desired position for the object panAxis to an angle
// newAngle, using the setPosition method in the

// ESC629ERAxisController class
```

For additional information on the Java programming language a useful reference is the tutorial on the Sun website: http://java.sun.com/docs/books/tutorial/. For more specific questions on the various built-in classes and methods simply go to the first website found by Google by searching the name of the class or method followed by "java". This should bring up an in-depth explanation from Sun Microsystems.

The first step was to write a driver for the Real Time Devices ESC629ER Motion Control Board. This driver manages binary signals to and from the board by utilizing methods that simplify reading and writing data bytes to the two LM629 control chips in the board. Our first board had to be sent back eventually because it had a defect that was giving us a great deal of trouble in our programming. Most of the difficulty in writing the driver was the way that data bytes must be written and read from the LM629 control chips. The chips must first be switched into COMMAND mode, sent a command byte, switched back into DATA mode, and then the data bytes can be read or written. After sending a command byte of sending/receiving a second byte of data, a bit in the status byte is set to logic HIGH and a method must be implemented to wait on this bit to return to logic LOW before continuing to read or write to the LM629 chips.

Another class was made called "ESC629ERAxisController" that would create an object for one of the controller axes. In this class there are methods to set up initial conditions for the motors (such as homing and setting up initial parameters). There are other methods to change parameters during operation such as desired position and velocity and interrupts. This class also has a "doControl" method that updates the necessary trajectory parameters and is continuously run during robot operation.

To get the robot head working with the input devices (joystick and/or slider board) an "embedded main" is run on the PC/104 computer and a separate simulation class is run from a secondary working computer. The two computers are connected via TCP (Ethernet). Both input devices are connected to and detected by the working computer and this is where the Yobotics! Simulation Construction Set GUI is run. Data is constantly updated for all the "YoVariables" in real time and graphs can be created to show and compare variables. YoVariables are a special type of variable implemented by the Yobotics! Simulation Construction Set. Classes were created called "BucknellHeadOneSimulation" and "BucknellHeadOneEmbeddedMain" to serve these purposes. Another class, "BucknellHeadOneController", is essentially a code representation of the head system. It sets up the axes on the ESC629ER board by creating two ESC629ERAxisController objects (one for each motor). There is a BucknellHeadOneController object is created in the embedded main that controls and represents the entire robot head setup. See code for more detailed information and documentation.

Compiling and Running the Software

See User's Manual for in-depth instructions

Explanation of Controls

Currently, there are three control modes set up for the Robotic Vision Platform. All three modes are accessible through a single jar file, "EmbeddedMainGyro.jar." Modes are selected by adjusting the MODE dial on the right side of the joystick. The first mode uses input from a MEMSense gyroscope mounted on the back of the base plate of the RVP. Rotational data from the Z and Y axes of the gyro are used to stabilize the RVP when rotated. This is done simply by setting the desired positions to the opposite of the rotational position: i.e. if the gyro reads 0.5 radians in the Z axis, the pan will be set to -0.5 radians. In addition, control from the joystick is overlaid on top of the gyroscope control. This allows for the operator to control the position of the cameras while maintaining a stable image.

The second control mode works the same as primary control mode but without the gyro control and more sophisticated joystick control. In this mode, the joystick is by default set to control the velocity of the head. So if the joystick were to move to the left, the head would rotate counter-clockwise for as long as the joystick was held in that direction. By holding down the "FIRE" button on the joystick the joystick control switches to position control. When the joystick is in the stable position the head is looking straight forward and the position of the head will adjust with the position of the joystick. A convenient feature of this is that if the head is desired to be returned to center, the user can simply hold the joystick in the stable position and hold the primary trigger. In this mode the gyro is still calibrated and the signals are displayed in the Yobotics! GUI but they are not used for any control.

In the first two modes the joystick throttle can be used to adjust the velocity and acceleration of the motor control.

Lastly, the third mode is set to control the RVP based on the position of the mouse on the screen. The X direction moves the head in pan and the Y direction moves the head in tilt. This mode is intended to be a step toward attaining control from the gyro in the goggles. This gyro is connected to the mouse input and thus it would be able to control the head in this mode. An operator would not have to worry about using one joystick for the biped and one for the head.

Spring Semester Programming Issues

Most of the control for the head was carried over from the work performed by Kandler and Snyder while working at IHMC. However, some changes and additions had to be made to allow for additional features and changes in hardware. The first change was to adjust the encoder resolutions and gear ratios for the two axes. This was accomplished by adjusting variables in the Axis Controller class.

The controls (as previously mentioned) have become somewhat more sophisticated than the programming from the past summer. Originally the head could only be controlled by the joystick in "position" mode or with the existing gyro on the biped. More of the joystick inputs were explored to enhance the controls to the current capabilities.

Most of the programming this semester involved receiving and interpreting the data from the gyroscope. Several classes were imported from the YoboticsBiped project to take the raw signals and process those signals to get rotational data. These classes need to be cleaned up and "gutted" to remove any extra lines such as those controlling the various degrees of freedom on the biped. Only the gyro data was desired to be taken from these files.

The gyroscope has been giving a variety of problems. In general, the gyroscope can perform correctly but there are a couple issues that arise with the Z axis during control. The first issue occurs whenever the system receives a significant shock or vibration. Any shock causes the Z axis to make a slight jump depending on the magnitude of the shock. This clearly was not an issue with the head designed at IHMC since the biped experienced significant vibration during testing. The other problem is that the Z axis begins to drift when rotating quickly in a back-and-forth manner. This creates an offset which eventually gets the head "stuck" at the software limit in the pan axis.

Currently, another gyroscope is being purchased to ensure that the current gyroscope is not just a lemon. Further work needs to be performed to adjust the calibration properties which are currently set to those from the biped project files. Because the problems are limited to the Z axis it seems likely that there is some issue with the compass integrated into the gyroscope. More in-depth analysis of the code and variable adjustment needs to be performed to identify this problem. However, when the head is eventually mounted on the biped it will not need this gyro and can run off the existing gyro. This has already been proven to function properly during by testing done at IHMC with the previous iteration.

Overview of Projects –

RobotHeadControl– Primary project file

- *ESC629ERAxisController*
- *BucknellHeadOneController*
- *BucknellHeadOneEmbeddedMain*
- *BucknellHeadOneSimulation*
- *HeadInputDevices*

RobotConstructionSet – Contains reference files

- *RealTimeDevicesESC629ER*

SimulationContrustionSet – Contains reference files

SimulationConstructionSetUtilities – Contains reference files

Overview of Primary Classes –

RealTimeDevicesESC629ER – This is the driver for the ESC629ER Motion Control board. It handles all of the bytes to be sent or received by the board. The driver is generalized so that it is compatible with an ESC629ER control board regardless of the specific motors being controlled.

ESC629ERAxisController – This class is used to create two objects: one represents the pan motor and another represents the tilt motor. These objects contain simplified methods that often call methods from the driver class.

BucknellHeadOneController – This is a class representative of the Bucknell head. It creates the two ESC629ERAxisController objects and controls the desired positions based on feed from the gyro on the biped and/or joystick. The method "doControl" in this class is where adjustments would be made if a different type of positioning were desired.

BucknellHeadOneEmbeddedMain – This is the class containing the main that is run on the PC/104 computer platform. It sets up and creates the YoVariables for yaw, pitch, and roll. A BucknellHeadOneController is also created in this class.

BucknellHeadOneSimulation – This class sets up the Yobotics! Simulation Construction Set GUI. The GUI can be used to display and compare variables. The joystick and slider board are set up in this class.

HeadInputDevices – This is the class used in the BucknellHeadOneSimulation class that links either the slider board or the joystick to the head. The code is written such that the slider board or joystick will only work if detected by the computer; otherwise, it will not affect the program.

Statement of Ethics

There is a substantial amount of controversy surrounding defense-related research, particularly in the university setting. This team feels, however, it has acted in an ethical manner and that this project is ethical. The team has followed each of the seven ASME Fundamental Canons.

The first fundamental canon provided by ASME dictates that the robot should ensure the safety of the public. The purpose of the fully developed robot is to operate in an urban society and provide reconnaissance remotely. This robot is not designed to kill, destroy or hurt human beings in any way, in accordance with ASME's 1st fundamental canon. Additionally, in accordance with the second canon, we have only done engineering work within our area of expertise. When the team did not feel comfortable designing a component, the team consulted specialists. Primarily, Jeff Gum, was of great assistance in matters concerning electrical components. Also, Jason Geist, Brent Noll, Dan Johnson, and Matt Tanner greatly assisted in the fabrication and design of the mechanical components. In terms of analyzing the programming, John Carff and Jerry Pratt were consulted. Component manufactures were also contacted to help troubleshoot problems and suggest set-ups. Finally, our advisor, Prof. Shooter, was also consulted for safety and design calculations and general questions throughout the design process.

The third through fifth canons are as follows: to continue their [engineers] professional development throughout their careers and shall provide opportunities for the professional development of those engineers under their supervision, to act in professional matter for each employer or client as faithful agents or trustees and shall avoid conflicts of interest, and to build their professional reputation on their merit of their services and shall not compete unfairly with others. These three canons were not relevant to this design project. The sixth canon states that engineers should only associate with reputable persons and organizations, and this was also followed. Finally, as canon 7 states, engineers should issue public documents truthfully and objectively. This document satisfies both of those criteria.

The major source of controversy with this robot is that it would dehumanize the act of killing by having a remotely controlled robot commit the act. This robot, however, is not intended to be used for warfare, but for reconnaissance and intelligence gathering, only. In addition, if used for its prescribed purposes, the biped will save the lives of many men and women who serve in our armed forces. In its current form and intended use as a demo for the IHMC biped, the RVP has little risk of causing damage or injury. This robot will be passed along to other engineers and they will be held responsible to similar, if not the same, code of ethics. For our purposes, we must trust our best judgment and the judgment of those in our military to appropriately use what we have developed.

Statement of Analysis of Safety

Safety is a key part of the design process. It is extremely important to design for safety when designing a piece of equipment that will be used as a demonstration but also involving expensive equipment. The safety of the people interacting with the robot and the protection of the equipment were considered in this analysis. To protect bystanders, there is a helmet built around the equipment. If something were to break and eject off of the body of the vision platform, the shell would block this piece from hitting anyone. Also, the helmet protects people from putting their fingers inside and getting them caught on moving parts.

The team members also designed to protect the equipment. A minimum factor of safety of 2 was used in the motor calculations to compensate for any friction in the system, inaccurate assumptions, and other inaccuracies in calculations. When the final calculations were done and the motor was specified, the factor of safety was higher than 2. The final design calls for a gearhead with a 50:1 ratio which yields a factor of safety of 7.35 for the tilt torque and 3.67 for the pan torque. Additionally, the moment of inertia calculations estimate a shell weighing a generous 1 pound. The helmet is designed to be as light as possible and is also made from carbon fiber so it will likely weigh much less than this. Additionally, one extra bearing of each size is being ordered, as well as a range of sizes of belts to ensure that the vision platform will work exactly as it should.

Furthermore, calculations were performed to ensure that the belts would not break by the loads applied by the motor and gearhead. The stall torque was used in calculating the maximum torque that the motor could supply to account for the worst case scenario. The stall torque is rated to be .08 N-m, and when the gearhead is considered, a 4 N-m torque could potentially be inflicted on the pulleys (Table 7).

Table 7. Maximum Torque Calculation

Stall Torque	0.08	N-m
Gear Ratio	50	
Max Torque	4	N-m

The force that would be felt by the belt was determined by the maximum amount of torque the motor could supply, 4 N-m and the radius of the pulley (Table 8).

Table 8. Potential Force Applied on Belt

Diameter of Pulley (in)	Diameter of Pulley (mm)	Force Felt by Belt (N)
1.003	25	314
1.2	30	262

The breaking strength of the pulley was rated at 86 N per mm of width. It was determined that a 3 mm belt would not be able to handle the forces that the motor could apply for either size pulley (Table 9). A 6 mm pulley has a factor of safety of almost 2 for a 1.2" diameter pulley and 1.6 for a 1.003" diameter pulley. Considering that the motor should never be running at its stall torque, a 6 mm belt width with a 1.003" diameter pulley should be more than satisfactory for this application.

Table 9. Belt Breaking Strength Analysis

2 mm Pitch			
		Actual Force on 1.003 in Pulley (N)	Actual Force on 1.2 in Pulley (N)
		314	262
Width (mm)	Breaking Force (N)	Factor of Safety for 1.003 in Pulley	Factor of Safety for 1.2 in Pulley
3	258	0.82	0.98
6	516	1.64	1.97
9	774	2.46	2.95

This design includes expensive and fragile equipment. A number of measures were taken to ensure that this head would be run sustainably and would protect the components. Calculations were performed to ensure that the motor would not overheat. The terminal resistance of the motor and the torque constant were used to calculate the current (Equation 3).

$$I = \frac{M_o}{K_M} \qquad [3]$$

where:
I is the current [Amps]
M_o is the loading torque [mN-m]
K_M is the torque constant [mN-m/amp]

From the current through the motor and the resistances in the motor, the temperature increase can be obtained (Equation 4).

$$T_{inc} = I^2 R * (R_{TH1} + R_{TH1}) \qquad [4]$$

where:
T_{inc} is the increase in temperature across the motor [K]
R is the terminal resistance of the motor [Ω]
R_{TH1} is the thermal resistance from windings to case [K/W]
R_{TH2} is the thermal resistance from case to ambient [K/W]

The motor parameters were provided by MicroMo (Table 10).

Table 10. Motor thermal parameters

	Variable	Value	Unit
Torque Constant	KM	26.1	mNm/amp
Toque at Winding	Mo	436	mNm
Thermal Resistance, thru motor	Th1	3	°C/Watt
Thermal Resistance, case to ambient	Th2	15	°C/Watt
Terminal Resistance	R	7.1	Ohms

From these parameters the current and thus, the temperature increase were calculated.

Table 11. Current through motor and temperature increase

Current	0.059913	amps
T_{inc}	0.458745	°C

It was found that the increase in temperature operating at normal conditions would be less than .5°C, or about an increase of .9 °F. This was said to be an acceptable increase in temperature. This should not cause any damage to the electrical equipment.

Statement of Sustainability

This particular project was not focused on sustainability, however, it was considered in part, in the design process. Most of the components of the RVP were made from aluminum, which is easily recyclable and is easier, and less invasive to mine than other metals. Additionally, material use was minimized. Aluminum was chosen to be as thin as possible while still maintaining the structural integrity of the RVP. The material that was used in construction of the RVP was often taken from scrap material already in the Product Development Lab at Bucknell.

Sustainability was also considered in developing the testing apparatus. A recycled backpack from a former senior design project was modified, instead of purchasing a new backpack and thus wasting more material. Extra molding from Professor Shooter's house was mounted onto the backpack to create a stable platform to support the RVP.

Testing Procedures

Testing of Previous Designs

A list of testing procedures to verify the critical specifications of the previously designed vision platforms are defined below. The values obtained in this testing will be compared with the vision platform that is currently being designed.

Specification: Torque

1. Attach a force gauge or spring scale at points noted in Figure 37 and Figure 38.
2. Run motor until stall
3. Repeat for several motor voltages (DC motors only)
4. Torque is calculated from $\tau = Fxr$

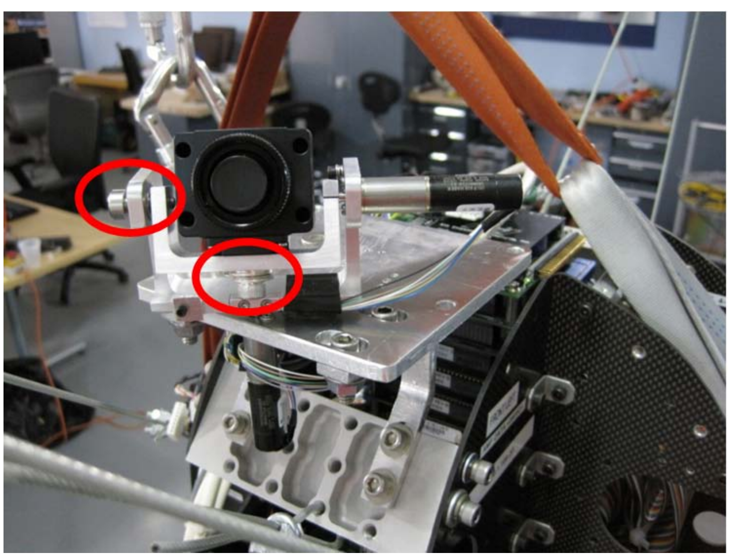


Figure 37. IHMC head design testing locations

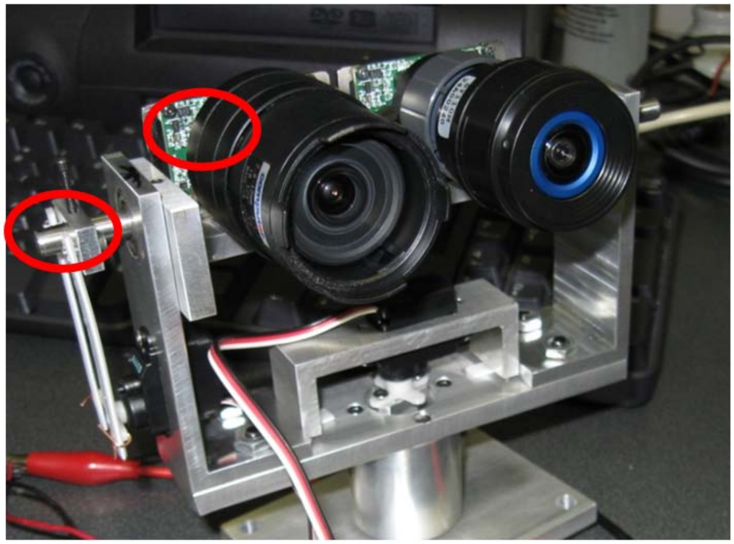


Figure 38. Bucknell head design testing locations

5. Specification: Speed/Acceleration
6. Move head at max speed. Do pan and tilt both separately and simultaneously
7. Record encoder data on IHMC head during movement to find position, velocity, acceleration
8. Use video camera to record movements of IHMC and Bucknell heads. Use MaxTraq to find speed and acceleration of Bucknell head and verify encoder data on IHMC head.

Specification: Power
1. Remove camera from IHMC head
2. Attach spool and string to shaft of horizontally mounted motor
3. Attach mass to other end of string, hang off table
4. Measure time required to pull mass up set distance   P=Fd/t
5. Repeat for several motor voltages

Specification: Durability
1. After completion of other testing, set up both heads to run back and forth for a set period of time
2. Periodically monitor heads to inspect for damage, wear, or other problems with components

These plans were not acted upon because of issues with the joystick in the Rittase/Sirot design and issues with the PC\104 board in the Kandler/Snyder design. Because the team was familiar the basic benefits and drawbacks of each design, it was determined that time was better spent designing the next iteration instead of testing the old designs.

Specification Testing

Testing procedures were developed for each of the specifications that were identified at the beginning of the project 8 months ago (Table 12). Additionally, it is imperative that the head can compensate for the motion of walking. Testing procedures were also developed to examine this feature. The RVP was first tested without a helmet and then again after the shell had been manufactured.

Table 12. List of Specifications

Specifications	Value
Size	smaller than 8”x8”x 10” (DxWxH)
Weight	4 pounds
DOF	2
Min. Speed	200 rpm
Min. Acceleration	1800 deg/s^2
Accuracy of Positioning	Less than 1^o
Resolution of Positioning	.01^o
Range of Motion	180^o pan, 150^o tilt
Number of Cameras	4
Camera Frame Rate	30 frames per second
Field of Vision	60^o
Resolution	640 x 480

Size
Use ruler.

Weight
Place on scale.

Speed
The RVP was set at an acceleration of 100 rad/s^2 and moved back and forth within its range of motion. Encoder data was used with the Yobotics! software in order to record position with respect to time. Speeds were determined using the known gearing ratio and taking the derivative of the position data for both the pan and tilt axes. The speed appeared to be limited by the range of motion allowed and a wider range might allow for higher speeds.

Acceleration
Accelerations were determined using similar techniques as were used to determine speed, however, to obtain the acceleration the second derivation of position was taken.

Accuracy of Positioning
Position the head to move just before the hard stop. Gradually move the head towards the hard stop in increments of .5^o. Keep moving until the hard stop is hit and record distance travelled to get there. This can be compared with the distance that the computer believes it has travelled to compare. This was not completed yet.

Range of Motion
Measure distance from hard stop to hard stop for each DOF.

Camera Frame Rate
Point Grey software will display frame rate. This can then be compared to the specifications listed.

Field of Vision
Turn on cameras. Mark off in the room the locations that the very last edge that the camera can see. Measure this distance to the center of the head and determine the radius. From this the angle can be determined using the equation 2*tan((W/2)/D) where D is the depth to the surface and W is the horizontal width.

System Testing

Compensation for Walking

It was important that the head be able to compensate for the motion of walking. The head was sitting on an aluminum stand and a wooden frame was constructed and placed on a backpack. The head was placed on the wooden frame and secured. One of the members of the team will walk around with the backpack and the gyro will be tested to see how well it can compensate for this walking motion.

The gyro on the head reads information as the head is tilted and sends this information back to the PC/104. This will cause the cameras to compensate for the motion of the head and this will be measured based on the output of the cameras on the head. The cameras need to compensate for side-to-side (yaw) motion of the walking robot as well as up-and-down (pitch) motion. The design did not account for roll, or twisting motion, and thus this will not included in the testing of the device.

Results

Specification Results

The Robotic Vision Platform was tested against the specifications. These tests needed to be performed without the helmet because the helmet was still in the process of being fabricated. The addition of the helmet would have only altered the dimensions, weight, and dynamic characteristics slightly. The results for each specification test were tabulated (Table 13).

Table 13. Testing Results (insufficient results in red)

Specifications	Value	Tested Value w/o Shell
Size	smaller than 8"x8"x 10" (DxWxH)	7"x9"x8.5"
Weight	4 pounds	4.82 lb
DOF	2	2
Min. Speed	200 rpm	94.5 rpm
Min. Acceleration	1800 deg/s^2	6916 deg/s^2
Accuracy of Positioning	Less than 1^o	N/A
Resolution of Positioning	.01^o	.004^o
Range of Motion	180^o pan, 150^o tilt	+/-175^{o}pan, sufficient tilt
Number of Cameras	4	4
Camera Frame Rate	30 frames per second	30
Field of Vision	60^o	39.0^o
Resolution	640 x 480	640 x 480

Not all of the original specifications were met. The size is roughly within the initial constraint but does exceed its specified width. Additionally, the head weighs roughly .8 lb more than was intended. The design was on course to achieve 4 lbs or below but electronic equipment, changes to the motor/gearhead piece, changes to the base, and other issues added unexpected weight. Though this is significant, there are ways that the weight can be reduced which are discussed in the Future Work section.

The speed and acceleration were testing for each of the axes. The pan axis showed slightly slower speeds and accelerations (Figure 39). The tilt axis moved a little bit faster (Figure 40). This is likely due to the additional gear reduction introduced in the pan by the pulleys.

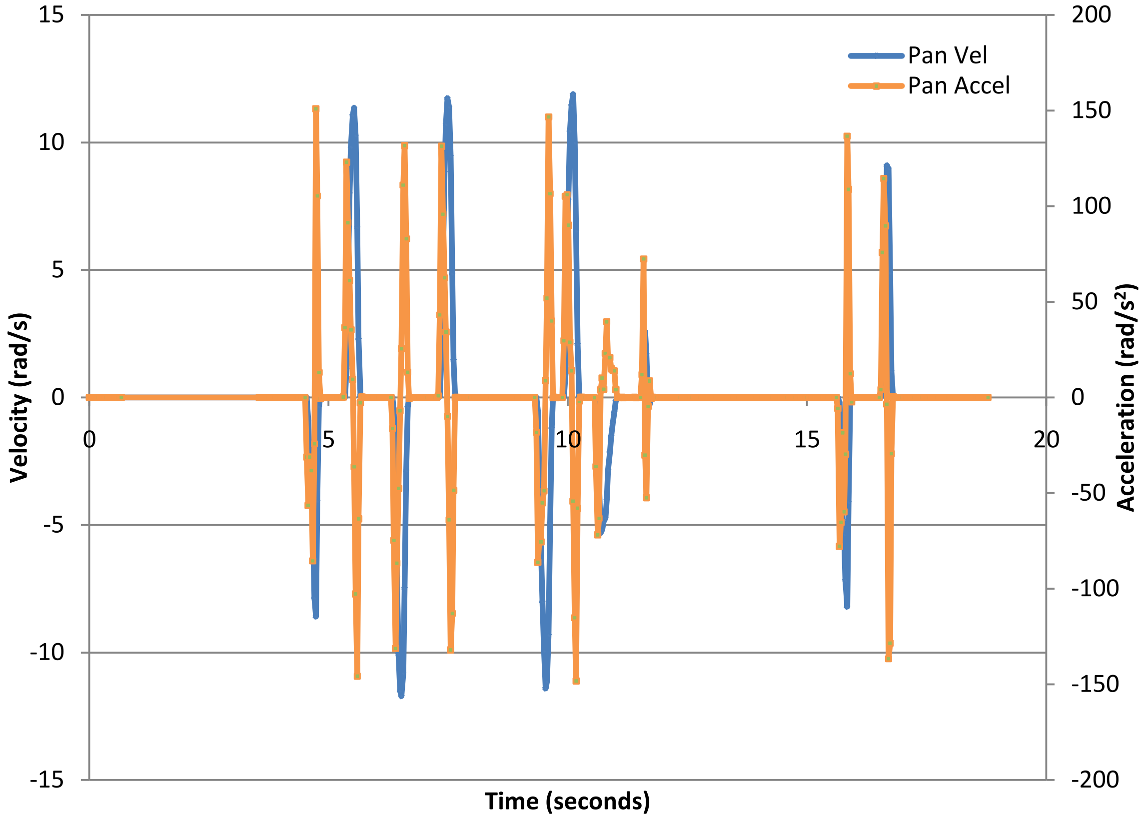


Figure 39. Measured Velocity and Accerleration for the Pan Axis

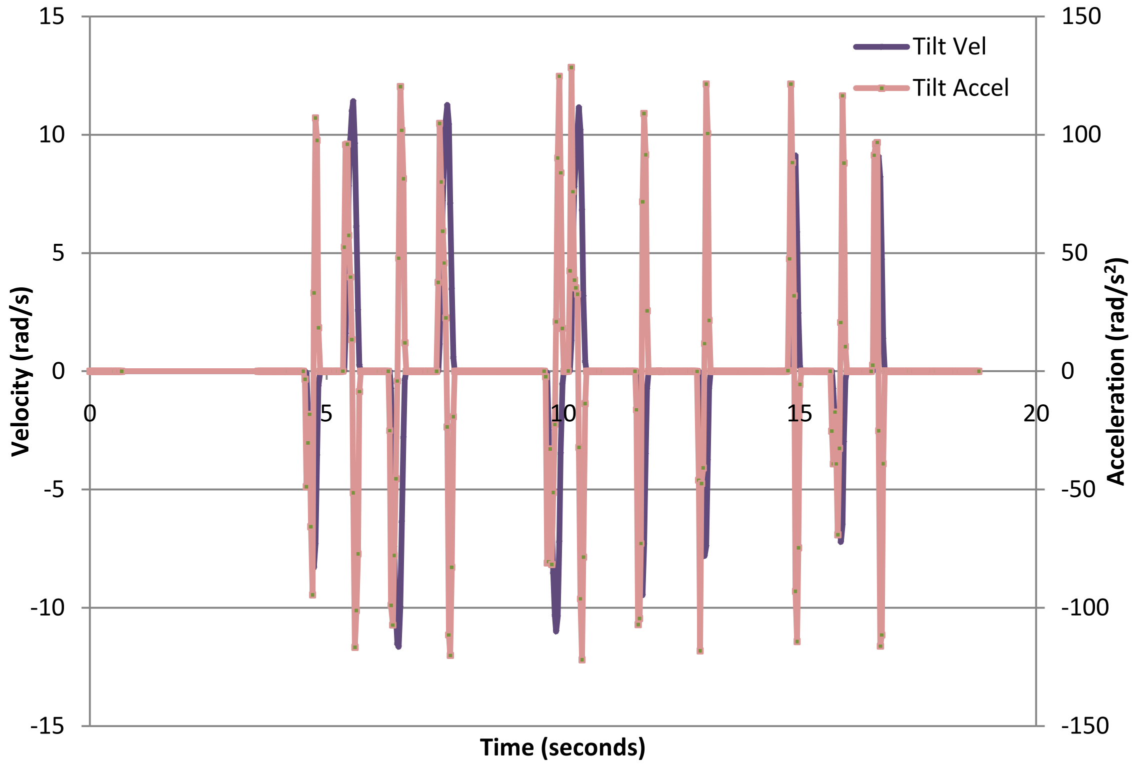


Figure 40. Measured Velocity and Accelerations for Tilt Axis

The speed originally specified was 200 rpm. The maximum speed obtained was only 95rpm. This was most likely due to the limited range of motion. As can be seen, the acceleration was significantly higher than specified, reaching 6900 deg/s^2. It appeared that the RVP could attain higher speeds if it had more time to reach them. Additionally, 95 rpm appeared to be sufficiently fast and if it were to go faster, it would likely cause the operator discomfort. This high acceleration is expected to be able to reduce the "shake" in the camera view to only high order vibrations. These can be completely eliminated by introducing image stabilization software.

Finally, the field of vision was less than originally expected. The field of vision was only found to be about 39°. A picture was taken of a white board at a fixed distance away (Figure 41). The width of the actual white board was compared to the distance away from the cameras to determine the field of vision using simple trigonometric relationships (Table 14). The 60° figure was just an estimate based on the cameras which were used over the summer, but it appears as though the 40° field of view was sufficient for the operator to get a good view of his surroundings without much distortion of the image. If it were desired to have a greater range of vision the camera lenses could be easily replaced for ones with a greater field of view. This was not done because of the significant distortion introduced by increasing field of view.

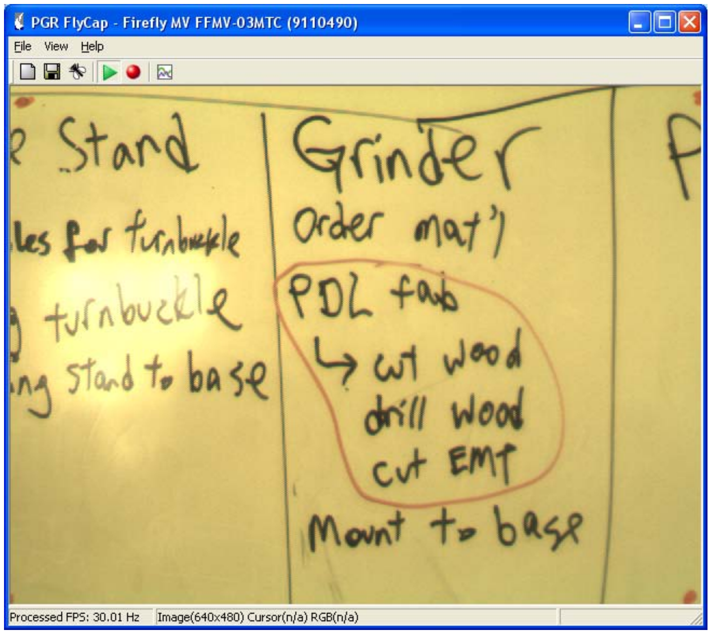


Figure 41. Field of Vision Testing Screenshot

Table 14. Field of Vision

Distance from Lens	24in
Width	15.75 in
Horizontal angle	39.0°

System Results

The overall system test could not be performed because of problems with the gyro described in the programming section. It is likely that full system testing will not be able to be performed until the head is delivered to IHMC and testing can be done while mounted on the biped. The issues with the gyro should not be present in that setup. However, the results from the testing thus far supports that there will be positive results from complete system testing. As stated the accelerations are more than sufficient and should be able to compensate for any major movements.

Future Work

In the future, it would be ideal to attain the values listed in the beginning of the project. Primarily, the size and weight of the RVP need to be lessened. A number of solutions could be implemented to reduce the weight. Pockets could be drilled into the pan base on the opposite side of the motor. Additionally, the motor and gearhead connection pieces are fairly hefty. These pieces were made thicker because of unexpected dimensions of the gearhead. If the gearheads had been in the lab before the gearhead and motor connection piece was designed, this unexpected weight could have been avoided. Finally, in practice there only needs to be 2 cameras, unlike the currently mounted 4 cameras. The Bumblebee2 camera is a substantial portion of the weight, at .75lbs. If this camera system could be eliminated, it would almost bring the RVP down to its specified weight. However, a main consideration in this design was robustness and versatility. A platform which could test multiple camera sets was ideal, so if the Bumblebee2 is not required, the weight requirements would be much easier to make.

The Fire-I cameras in the final design were selected in order to get the system up and running before the date of the design exposition. More time should be put into selecting cameras. It is thought that the only problem with the Firefly MVs which were used previously was that their signal output was not compatible with the stereoscopic multiplexor. There may be other cameras which may be smaller, fit better, and give a wider field of view with interchangeable lenses. More research should be done in order to select appropriate cameras.

Other additions for future work could be the addition of sound – both a microphone for the user to hear the surroundings and a speaker for the user to communicate with them. The Bumblebee2, if used, should be incorporated somehow (possibly for object tracking). Right now, it is not being used at all, so someone should use it appropriately or not use it at all.

The programming side of the project still leaves room for future work as well. These issues include getting the gyroscope to function properly and consistently and working on enhancing the level of control. It would possible and useful to include an algorithm that could account for translational movement using simple trigonometry and knowledge of depth of view. Though it is far beyond the scope of this project, there is also significant room for programming based on the camera signals. It may be useful to develop object recognition and tracking that can be used to help the biped recognize something like a step or doorknob. This would greatly enhance the capabilities of the biped.

Lessons Learned

This project has been helpful to each of the team members on multiple levels. The team has learned a lot about working in a team and communication. Communication was critical amongst the team, with the customer, and with the project coordinator. Communicating with IHMC was helpful because they were extremely clear about the components that were important to them and those that were unnecessary. Because this is an ongoing project, we had to ensure that our design was compatible with the equipment at IHMC. Despite our infrequent meetings with them, they were very clear about the specifications that were valuable to them.

It has been extremely difficult to manage time amongst the team which made communication difficult from time to time. When working alone, a schedule is much easier to organize, but working on two or three group design projects simultaneously made meetings extremely difficult to organize. Being flexible and adjusting to the needs of our teammates was integral in our success. As long as we went about scheduling meeting times in a cordial manner, things never got heated. The buzzwords for good teamwork, especially in a senior design team, are flexibility and respect.

Though we have worked on many projects at Bucknell, senior design has been our first project that has spanned an entire semester. Because of this, we have had to learn to allocate time to meet frequent deadlines. One of the biggest challenges with meeting deadlines was finding a way for the entire group to meet. Sometimes we had to meet at inconvenient times or only for a short while. These short work periods were usually not very productive. The bulk of our work was done during longer work periods where we felt like we had enough time to dive more deeply into the work. In general, we tried to find a way to keep everyone updated rather than just breaking up the tasks and having each member only aware of their own direct work. Sometimes this would cause us to slow down on decision making. From this, we learned that it was important to use our individual time more effectively and trust and rely on the other members of the group to complete their tasks. In order to get tasks accomplished we found that we do not all need to meet but sometimes breaking up into smaller groups can be more efficient.

Additionally, the team has gained a lot of experience specifying motors, researching transmission systems, 3D vision, and designing for manufacture. The design required many hours analyzing various websites and catalogs to specify the appropriate motors and gearheads. The calculations were fairly simple but actually finding a motor that fit the specifications was rather challenging and frustrating. It was essential to realize that these kinds of decisions take time. As we're always told but sometimes don't like to put into practice, patience is a virtue. Anything of quality takes time and effort.

Another aspect of the design process that gave us some troubles at first was conveying design concepts to each other without any 3-D models. While trying to make decisions, like how to mount the motors are design the pan shaft support, we would discuss concepts and draw a lot of 2-D drawings on the lab whiteboards. Often times this method led to confusion and misunderstanding. When we were able to create actual models it was much easier to convey the information and make decisions. Also, it can be difficult to notice possible problems when just referencing a drawing.

Implementing the 3D stereo video proved to be a frustrating exercise. This is largely because we were trying to push through using camera systems that were bought in the summer before the team was formed, with no clear path on how to achieve stereo video. 3D goggles and software were later chosen under the assumption that the PGR cameras were sufficient without checking for format compatibility (another concept that was not fully understood). Simple webcams proved to be more compatible than the expensive cameras, a realization that took months to come to, which was much needed time that could have benefitted other parts of the project. If starting over, it would be essential to check to make sure that all electronic components are compatible with each other before investing time and money in them.

Allocation of Work

Scott Bevan – Initial and final shell design, part drawings, selected belts, microphones, carbon fiber, speakers, 3D goggles, fabrication, shell fabrication

Matthew Kandler – Assembly, designed shafts, specified pulleys, camera lenses and bearings, fabrication, programming

Danielle Renzi – motor calculations, specified gearheads, thermal analysis, sustainability analysis, bill of materials, fabrication, design & fabrication of testing apparatus

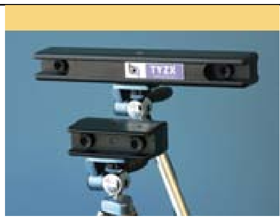
William Rittase – Drawing files, specified motor, motor assemblies, exploded view, fabrication, shell design, shell fabrication, emotional support

Appendices

Appendix I. Stereo Vision Camera and Goggle Research

Stereo Vision Cameras

Brand/Product	***Description***	***Cost***
Bumblebee 2.0 BB2-03S2 	• IEEE-1394 FireWire Interface • Sony 1.3" progressive scan CCD • 12cm baseline • 648x488 at 48fps • 342g • 2 x M12 microlens mount • 157 x 36 x 47.4 mm • http://www.ptgrey.com/products/bumblebee2/index.asp • Point Grey	$2,000
Surveyor Stereo Vision System 	• Headers for 8 servos • 512x384 at 43fps 48 disparity • GPL Open Source, basic processing features • WiFi through antennae • Exposed circuit boards • Built in dual motor driver, 1A per motor • http://www.surveyor.com/stereo/ • Surveyor Corporation	$550
PCI/104 nDepth™ Vision System 	• PCI/104, camera, lenses, cables, software • 6cm baseline • 752x480 stereo vision camera • 30fps 92 disparity • 1/3" wide-VGA CMOS digital image sensors • 4.25 x 1.5 x 1.25 in • G2 system creates 3D object maps • http://www.focusrobotics.com/docs/focus_ndepth_pci_brief.pdf • FOCUS robotics	$3,995
DeepSea Stereo Cameras	• Used on Stanford Little Dog http://www.stanford.edu/class/cs229/proj2007/Kim-GettingThePositionAndThePoseUsingStereoVision.pdf • Range 40, 62, 83 HFOV • Aptina MT9V022 CMOS imagers • 3cm, 6cm, 8cm, 14cm, 22cm, 33cm baselines • 512x480 at 200 fps	$4,995

	• http://www.tyzx.com/PDFs/Tyzx%20DS%20Cameras.pdf * TYZX	

Video Goggles (HMDs)

Name	***Description***	***Price***
i-glasses 920 3D 	• Resolution: 920,000 Pixels Per LCD • Aspect Ratio: 4:3 • Color Depth: 24 bit color • Field of View: 35 degrees diagonal • Video Input: Composite A/V • Video Input Format: NTSC/PAL/SECAM • 3D Video Format: Interlaced 3D Video • Audio: Double Channel Stereo • Power Supply: 1,000 mAh Rechargeable • Battery Life: Approximately 3.5 hours • Weight: 2.4 ounces	$379.95
i-glasses i3TV 	• Resolution: 800 x 600 • 1.44 Million Pixels per Display • Field of View: 26 Degrees Diagonal • Virtual Image Size: 70" at 13' • Color Depth: 256 Levels per Color (True 24 Bit) • Contrast Ratio: 75 to 1 • Focus: 13' TBR • Eye Relief: 25mm • Exit Pupil: 17mmH x 6mmV • Convergence: 7'10", 100% Overlap, TBR • Refresh Rate: Flicker Free 100hz display rate • Audio: Full Stereo • PAL/NTSC/SECAM: Composite or S-video Input • Input Frequency: 50 or 60 Hz (25 or 30 Hz Interlaced)	$899.95
eMagin Z800 	• Resolution: 800 x 600 • Pixels: 1.44 Million Pixels per OLED Display • Colors: 16.7 Milllion • Field of View: 40 Degrees Diagonal • Virtual Image Size: 105" at 12' • Tracking: Built in 3-axis head tracking (1 deg accuracy) • Inputs: VGA frame sequential 3D video, 60 Hz, dual input version available • Compatibility**: Win XP, most ATI and Nvidia cards • Extras:: Built in headphones and noise cancelling microphone, custom colors • Weight: 8 oz headset	$1499 Sale $1299

Visette Pro 	• Resolution: 640 x 480 • Pixels: 920,000 Pixels per Display Field of View: 60 Degrees Diagonal • Eye Distance: 60-70 mm adjustable • Stereo: 2 independent channels (no sync needed) • Inputs: VGA, Composite NTSC or PAL Weight: Approx. 840 g (incl. battery) Adjusts to Fit all Individuals • Control Features: On / Off, Brightness, Contrast, Focus and IPD • AC Adaptor Included: 110-130V AC or 220-240V	$3995
CyberMind Visette45 SXGA 	• Dual Input SXGA (1280x1024) • 45 deg FOV • Can pretty much customize to whatever you want	$12,900
Kaiser ProView SR80 	• Dual Input • 80 deg FOV • Fits 5% of females, 95% of males • If you care to know more, see the price.	$27,500

Multiplexer (3D Encoder)

Name	***Description***	***Price***
Dimension Technologies Inc 3D Video Encoder	Two video inputs s-video output Either field sequential or side by side	$2500

Appendix II. Vision Platform Requirements

Objectives:

1. Physical Head Characteristics – humanlike head
    a. Height – humanlike about 18.7 cm (7.4 inches)
    b. Width – humanlike about 15.1 cm (5 inches)
    c. Eye distance – humanlike about 6.1 cm (2.4 inches)
    d. Weight – less than 4.25 lbs (Mertz head weighs that) – minimizing weight reduces load on actuators and can increase reliability. Also reduces weight on biped.
    e. Degrees of freedom – 2- turn and bob (pan and tilt) – robonaut has side tilt but found it unnecessary and don't use it. If head moves, do eyes have to?
    f. Vibration isolation?
    g. Aesthetics –
        i. Helmet, humanlike or other?
        ii. Characteristics that make face have more humanness are eyelids, nose and mouth (source diSalvo). Note: these aren't functional for our application.
2. Vision characteristics
    a. Binocular? A lot of them out there use 2 cameras
    b. Control
        i. Focus
        ii. Aperture – for variation in lighting
        iii. Vergence – if using two
    c. Motions – do we need eyes to move independent of the head
        i. Pan:
            1. + or - 90 degrees? Half of full spectrum
            2. Speed: 180 deg/sec? Other heads seemed able to go 150 deg/sec
            3. Incremental resolution: 0.003 degrees (TRISH paper) Need to explore what is needed for isolation of body movements.
            4. Will need to compensate for 30 degrees of swing during walk to isolate image during body yaw
        ii. Tilt:
            1. +90 - 60 degrees? Can look completely up, but any lower would look at body
            2. Speed: 180 deg/sec (to have same as pan)
            3. Incremental resolution: 0.003 degrees (TRISH)
            4. Balance at "home" position
            5. Will need to compensate for 10 deg of tilt from body during walk.
            6. Strongly desired to use tilt to compensate for 7 cm of z translation of the body during walk. Will need to choose a focal distance for this. Maybe 2 meters.
        iii. Torsion:
            1. +- 10 degrees. Need to account for body roll during walk
            2. Speed 180 deg/sec (to keep the same) Not really needed as fast I would think.

            3. Incremental resolution: 0.003 degrees (keep the same)
        iv. Z translation
            1. Need to compensate for 10 cm of travel during walk
            2. Try not to translate the camera if we can avoid it.
            3. Try to compensate through tilt
    d. Cameras
        i. Resolution: Mertz has 640x480 24 bit color
        ii. Speed: Mertz is 30 frames/sec
    e. Communication
    f. Mertz uses YARP: an open-source vision code software with various libraries
3. Communication hardware and protocols
    a. Interface with biped
4. Situational awareness
    a. vision for tele-operation
    b. obstacle detection?
    c. location?
5. Human operator
    a. Work with Human-Robot Team navigation software

Basic

1. Fit on biped
2. transmit video to Carff system
3. provide pan, tilt and torsion

Performance

1. no bigger than human head (height 7.4 inches, width 5 inches, eye distance 2.4 inches)
2. Weight < 4.25 lbs (Mertz weight that)
3. Pan +- 90 degrees
4. Tilt +90 -60 degrees
5. Torsion +- 10 deg
6. Speed = 180 deg/sec?
7. Resolution 640 x 480, 24 bit color (nominal)
8. Capture speed need no more than 30 frames/sec
9. Isolation – small picture movement

Wow

1. Binocular
2. Controllable vergence
3. Cool looking head

Appendix III. Excerpt from Design of a Bipedal Walking Robot

Design of a bipedal walking robot.

Jerry Pratt[a], Ben Krupp[b]

[a]Institute of Human and Machine Cognition, 40 South Alcaniz Street, Pensacola, FL USA 32502
[b]Yobotics, Inc., 2138 Sinton Avenue, Cincinnati, OH USA 45206

ABSTRACT

We present the mechanical design of a bipedal walking robot named M2V2, as well as control strategies to be implemented for walking and balance recovery. M2V2 has 12 actuated degrees of freedom in the lower body: three at each hip, one at each knee, and two at each ankle. Each degree of freedom is powered by a force controllable Series Elastic Actuator. These actuators provide high force fidelity and low impedance, allowing for control techniques that exploit the natural dynamics of the robot. The walking and balance recovery controllers will use the concepts of Capture Points and the Capture Region in order to decide where to step. A Capture Point is a point on the ground in which a biped can step to in order to stop, and the Capture Region is the locus of such points.

1. INTRODUCTION

To date, there have been a number of three dimensional bipedal walking robots developed, such as the Honda P2, P3,and ASIMO[25,26], Sony QRIO[27], Waseda University Wabian[28], University of Munich's Johnnie[29,30], Kawada/AIST HRP-2[31,32], and others. Many of these robots are limited to commanding joint positions, rather than joint torques. This makes it difficult to perform complex tasks such as walking blindly over rough terrain, dynamically responding to unknown disturbances, or possessing the ability to capitalize on passive dynamic control strategies. Yobotics is developing a twelve degree-of-freedom bipedal walking robot platform, which has been dubbed M2V2 (see Figure 1). The robot will be capable of high fidelity force control at each of the 12 degrees of freedom. With the ability to go beyond joint tracking trajectories, M2V2 will be used to implement, validate, and extend various bipedal control algorithms including those developed on Spring Flamingo[1], a planar biped, and on a simulated three dimensional robot[2]. We believe that high fidelity force control is a critical requirement for graceful walking over rough terrain and robustness to disturbances. Our previous work with the robot Spring Flamingo[1,10,11] has shown that good force control leads to simple yet reliable algorithms for walking over rolling terrain. Figure 2 shows time lapse photos of Spring Flamingo in 1999 walking over alternating 15 degree inclines and declines without any prior information or sensing of the terrain besides the location of where its feet fall. To date we know of no other bipedal walking robot that has been able to repeat this feat. We credit Spring Flamingo's graceful walking, in part, to the force-controllable Series Elastic Actuators[33] at its joints. An improved version of these actuators are used in M2V2.

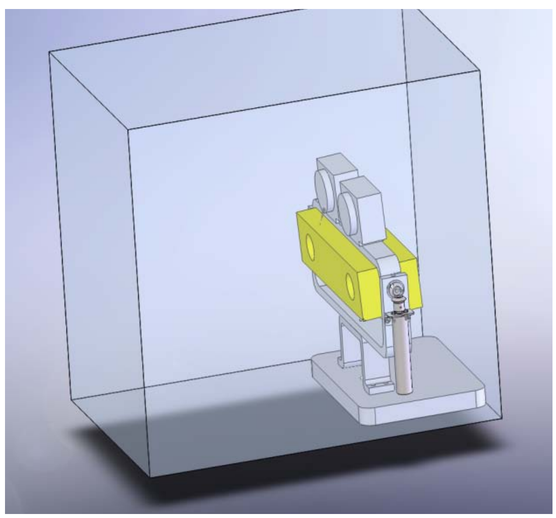
Appendix IV. Specifications

Size – smaller than 8in x 8in x 10in (DxWxH)

Justification: These dimensions are based on proportions of the human body and head from Da Vinci's *Vitruvian Man*. These dimensions were then checked against a typical human. Also, the width dimension needed to be able to fit the Bumblebee2, so it was increased slightly to account for a helmet.

Additionally the space needs to accommodate, at the minimum, all 4 cameras. We plan to use 1 Bumblebee 2 (47.4x157x36 mm (DxWxH)) and two Firefly MVs (24.4x 44x34 mm (DxWxH), each). The remaining space is shown below by the water box.

Validation Technique: Dimensions can be measured by hand once the RVP is made; before then, we can refer to the CAD dimensions.



Weight – 4 pounds

Justification: The average human head weighs around 10 pounds. However, this seems very high for a robot made of aluminum and cameras. We believe a Bumblebee2 and 2 Firefly MVs can be incorporated onto the head with aluminum supports and be around 4 pounds at most. The Bumblebee weights 342g (.75 lb) and the Firefly MV weighs 37.6 each (.082 lb). This gives us 3.086 lb for the motors and the mounting.

Validation Technique: The weight can be measured using a simple scale. During the design process weight can be approximated using volume and material density in CAD files.

DOF – 2

Justification: Pan and tilt are necessary for the operator to be able to look around the environment comfortably. During operation, the biped does not roll very much, so extra actuation is not required for this DOF.

Validation Technique: This can be measured by counting the number of actuators in the design.

Speed – TBD

Justification: We believe this value needs to be around 1200-1300 deg/s, as this is what the spec sheets for the motors on the IHMC head call for. These motors appeared to move quick enough for active stabilization of the image; it does not need to move any faster than this speed. Any faster would be overkill. However, we are not sure if the specifications match what the actual design is doing, so a test will be done later to determine how fast the system actually moves using the encoders.

Validation Technique: The final design will require some sort of encoders to give position feedback which can be used to measure the speed during operation. Both maximum and average speeds will be measured.

Acceleration – TBD

Justification: See above.

Validation Technique: See above.

Accuracy of Positioning – less than 1 deg

Justification: All of the zero-backlash motors give this as a specification. The IHMC head does not have a zero-backlash gear head, and it gives around 3 deg of backlash. This is simply too much play and the motor tends to "wiggle" around. A zero-backlash gear head is necessary for the next design.

Validation Technique: Any play in the motor is unacceptable.

Encoder Resolution – 0.01 deg

Justification: Most encoders will be able to produce a resolution that is much better than this target value, but this number serves as an upper limit. This number is based on the Harvard KTH and TRISH heads.

Validation Technique: This is a physical characteristic of whatever encoders we choose to use for the pan and tilt. The value can be found on the encoder specification sheet.

Range of Motion – 180 deg pan, 150 deg tilt

*Justification***:** We want to have the head turn and at least look off both of the shoulders for the pan. For the tilt, the operator has no use looking straight down at the body, but may want to look straight up. Therefore, 90 deg up and 60 deg down from the horizontal should be adequate.

Validation Technique: The range of motion may be limited by either the geometry of the head and some sort of hard stop or by software limitations. Once the design is finalized the ranges of motion can be measured by checking the limits on pan and tilt.

Number of Cameras – 4

*Justification***:** In previous meetings, the group has come to the decision to include the Bumblebee2 (with two cameras on it) and two of the Firefly MVs. This may change depending on interfacing between the PC104 and the cameras themselves.

Validation Technique: This is measured by counting the number of individual cameras on the final design.

Camera Frame Rate – 30 fps

*Justification***:** Current cameras and previous specifications call for 30 frames per second as minimum. This number is also what the human eye can interpret.

Validation Technique: This is a characteristic of whatever cameras are chosen to be used on the final design that can be obtained from specification sheets.

Field of Vision – 60 deg

*Justification***:** This number is based on the average FOV of the 3D vision goggles that we have been looking to purchase. We will resolve this further once we physically can subjectively test them in the lab.

Validation Technique: This is a characteristic of the type of camera and lenses that are used. The 3-D goggles will likely have a smaller field of vision and limit the system. To check the accuracy of the FOV from specifications we could use simple trigonometry with the camera images.

Resolution – 640 x 480

*Justification***:** The Bumblebee2 and Firefly MVs typically give off a 640x480 resolution image. This can be increased, but it lowers the frame rate and requires more processing power.

Validation Technique: This is also a characteristic of whatever cameras are chosen to be used on the final design that can be obtained from specification sheets.

Appendix V. Engineering Drawings

Appendix VI. 3D Stereoscopic Vision Components

Hardware:

- eMagin Z800 3D goggles http://www.3dvisor.com/support.php
    - Requires frame sequential video input through VGA in DirectX or OpenGL
    - 800x600, 60 Hz signal
- Dell Optiplex 960, Intel Core2 Duo E8600 @ 3.33GHz, 3.25GB RAM, Windows XP SP3
    - ATI Radeon HD 4670 graphics card with 512MB memory
        - Driver 8.561.0.0 (12/1/08)
- Point Grey Bumblebee2 Stereo Vision system http://www.ptgrey.com/products/bumblebee2/
    - (BB2-03S2C) Sony ICX424 CCD, 648x488 pixels, 48 fps
    - (BB2-08S2C) Sony ICX204 CCD, 1032x776 pixels, 20 fps
    - Image Formats: On-camera conversion to YUV411, YUV422 and RGB formats
    - Focal Lengths: 2.5mm with 97° HFOV (BB2 only) / 3.8mm with 66° HFOV / 6mm with 43° HFOV
- Point Grey Firefly MV cameras http://www.ptgrey.com/products/fireflymv/index.asp
    - 2x (FFMC-03M2C) Micron MT9V022 CMOS, 752x480 pixels, 61 fps, FireWire
    - (FMVU-03MTC) Micron MT9V022 CMOS, 752x480 pixels, 61 fps, Mini-B USB
    - Lenses??? CS-mount (5mm C-mount adapter included) • M12 microlense mount2
    - Video Data Output: 8 and 16-bit digital data
    - Image Data Formats: Y8, Y16 (monochrome), 8-bit and 16-bit raw Bayer data (color models)

Possible Options for 3D

- Purchase nVidia 5,6, or 7 series card with 3D drivers – unsure if newer cards support 3D output
    - Instructions in Z800 user manual, support from eMagin
    - Few more options/ adjustments
    - Use 91.3 Drivers – make sure forceware and stereo drivers are same

- **Try using 3rd party drivers from iZ3D with current ATI card http://www.iz3d.com/licenses**
    - **Talk to Charlie**
    - **Very little info or support base**
    - **Set s3D Mark to enable 3D**
    - **Need Direct X or OpenGL signal to activate 3D**
- **Use Stereoscopic player/multiplexer software from 3dtv.at**
    - **Combine multiple camera signals to one file**
    - **Play stereo video files to multiple output formats**
- Talk to Virtual Realities about an integrated system – Armand, ext 449
    - x Quest 3D development tool for real-time 3D apps
    - x TriDef Media Player
    - x Buy or upgrade to Dual input version ($2195) plus signal conversion box

Current Lab Set up: 2D works, 3D demo effect active but not synced/timed correctly

- Z800 goggles as second monitor from ATI card output (2D)
    - Use iZ3D driver (3D)
    - Force 3D using Lab Tool from eMagin

Home Set Up: 2D works, 3D demo works, 3D works automatically in Command and Conquer Generals, Age of Empires 3, 3D activates in Battlefield 1942 & 2, but computer locks up. 3D video works perfectly with 3dtv stereoscopic player and demo videos.

- Z800 goggles as mirrored monitor from Nvidia GeForce 6800 card
    - Use Nvidia 31.31 forceware and stereoscopic drivers
        - Set 800x600 resolution, 60hz
    - Play videos with 3dtv Stereoscopic player
        - Output to Nvidia Stereo signal

Appendix VII. Camera Lens Selection

There are a few requirements for the type of lens that will be used on the robotic vision platform. These requirements are compatibility issues with the Firefly MV cameras.

Firefly MV Specifications:

Image sensor type:	1/3" progressive scan CMOS
Mounting:	CS-mount or C-mount with adapter
Max resolution	752x480 @61 FPS
Mass:	37g

The maximum image sensor size for the lenses must be at least as big as the 1/3" sensor which should not be a problem since many C-mount lenses work with at least 2/3".

The only difference between C-mount and CS-mount is that C-mount has a 17.526mm flange focal distance and the CS-mount has a 12.52 flange local distance. This is the distance between the mounting flange and the firm place. CS-mounts typically a wider range of vision because of this shorter distance.

There are additionally some design specifications that are desireable and will serve as criteria for choosing the best camera lens. Weight is one of the most important concern, along with field of vision (FOV) and image resolution.

3D Visor Specifications:

Resolution	800x600 pixels
Diagonal FOV	~40 degrees

One important decision to make while choosing the camera lens is the type of lens. The two primary choices are either a fixed focal length lens and a micro-lens. The former would fit on the C-mount adapter and the latter would require an adapter. However, the micro lenses are much smaller and lighter and capable of producing high resolution. These micro lenses are also capable of viewing a wider FOV. When comparing larger lenses to the micro-lens it is important to note the maximum image sensor size. Lenses with larger sensor sizes give a FOV that is for sensors of that size. This FOV would be considerably decreased for smaller image sensors.

One of the primary concerns with this kind of lens was how to tighten the threading for the lens. To fix this issue, there is an adapter available with an o-ring. A concern that still needs to be addressed is how to fit the microlens on the camera at the proper focal length.

Possible lenses:

Image	Product	Cost	Focal Length	Angular FOV	Diameter	Length	Weight
	Edmund Optics "Compact Fixed Focal Length Lenses" NT56-526	$295	8mm	~35	30.5mm	27.0mm	48g
	Edmund Optics TECHSPEC® Megapixel Finite Conjugate µ-Video™ Imaging Lenses NT58-201	$75	6mm	~45	14.0mm	14.1mm	---
	Edmund Optics Infinite Conjugate µ-Video™ Imaging Lenses	$38	6mm	44	15.0mm	15.3mm	---

*Be sure that back focal length is greater than 4mm

Links:

Edmund Optics - http://www.edmundoptics.com/onlinecatalog/browse.cfm?categoryid=218

Appendix VIII - Gearhead Analysis

In light of a recent discovery that the specified gearhead is more expensive than anticipated, additional gearhead options are provided. The original specification of the gearhead was done under two assumptions. One was that the budget was flexible and cost was not a significant factor in design, and the second was that gearheads would not cost more than a $200.

The specified Harmonic gearhead, with a University discount, is going to be almost $600 each. While this is expensive, if accurate object recognition are an integral part of the design, this gearhead is absolutely necessary. This gearhead has two orders of magnitude less backlash than all the gearheads considered. It is one of the smaller and lighter options, has the highest speed and can withstand the necessary torque for the pan and tilt.

If, however, object recognition is not planning to implemented with this design, the more cost effective MicroMo and Moog gearheads will suffice.

	Harmonic Drives LLC	**Moog**		**MicroMo**		
	CSF-08-30-2XH-J	32 mm Precision Planetary Gearhead		"30/1S"	"26/1S"	26 A
Max Input Speed (rpm)	8500	5000		4000	4000	5000
Gear Ratio	30	29		23	23	40
Backlash (deg)	0.03	2		1	1	3
Weight (g)	111	210		139	116	23
Input diameter (mm)	3	3				
Max Torque		2500		6000	4500	1000
Cost	$596.00			$273.40	$215.80	$99.50
Resulting Speed (rpm)	283	172		174	174	125
Torque (mN-m)	480	464		368	368	640
FS Pan	2.2	2.1		1.7	1.7	2.9
FS Tilt	4.4	4.3		3.4	3.4	5.9

Notes:

Moog Gearhead:
This gearhead is roughly the same size as the currently speced gearhead (Harmonic Drives LLC) It is 61 mm long where the harmonic drives on is 51 mm long The shaft inputs are both 3 mm The faces of harmonic is 32mm x 32 mm and this isa 32 mm diameter weighs less but significantly more backlash

MicroMo:
The "S" signifies that it must be custom made from steel