Control System for Teleoperated Rock Sample Retrieval Rover

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***Abstract*—Autonomous and tele-operated robots been a crucial development in aiding the human exploration of outer space. Robotic systems allow scientists to learn about other celestial bodies without being physically present, which is greatly beneficial for areas where humans cannot survive. In this technical report, we report the development process of a tele-operated rover for retrieving rock samples at the NASA Johnson Space Center. Specifically, we present two of the most vital components of the rover: its control framework for movement and sample acquisition actions, and sensory transmission. An operator at the mission control room sends manual control commands over the network, to which the rover operates in a remote location. This rover design was selected as one of the finalists for the 2016 Exploration RoboOps Competition by NASA, and earned fifth place in the competition.**

Keywords*—*rover, controls, motion planning, automation

I. OVERVIEW

The University of Wyoming Rover Design Team was selected as one of the eight finalists to the 2016 RASC-AL Exploration Robotics Tele-Operations Competition (RoboOps) held at the Johnson Space Center (JSC) in Houston, Texas. This competition is sponsored by NASA and the National Institute of Aerospace, and asks university teams to design tele-operated rovers that will collect small, colored rock samples from the JSCs Rock Yard while remotely operated from the mission control at the respective university campuses.

The expected final product from each team is a fully mobile rover with a manipulator for sample acquisition, and must be entirely operated remotely over the Internet. In addition, the rover must satisfy the following physical constraints and specifications outlined in Appendix A: Design Constraints and Requirements section of this report.

This report will provide a background on our design process and competition strategy, a brief description of the overall rover system, a specific technical description of the control system, considerations noted during the design process, and a section for the outcomes and future work. The appendices include the official design constraints and specifications set forth by NASA, a schedule of the development process, a list of parts used in the design, and circuit diagrams for the onboard electronic components.

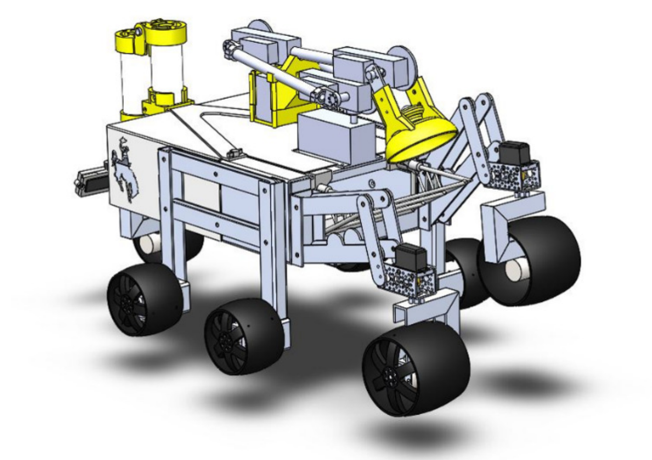

Fig. 1. 3D model of the suspension

II. BACKGROUND

Our team's strategy to this competition revolves around the age-old concept of divide and conquer. We field two rovers in hopes to cover vastly more territory and allowing for quicker acquisition of samples from a variety of terrains.

The two semi-identical rovers feature a unique shrimp suspension and drive system. This type of suspension is passive, requiring no control or power, as its designed around the basic mechanical elements of four-bar mechanisms assisted by springs. With the articulating elements in pairs and a single fixed rear wheel, the rovers are driven by seven gear-reduced DC motors, housed inside the wheels and protected by aluminum motor housings. The two main advantages of this system are its ability to adapt to the changing terrain while leaving the top of the rover free to mount a robotic arm.

Both rovers feature a four degree of freedom arm, mounted along the longitudinal axis of the rover. These arms are capable of rotating 360 degrees at the base and can reach the ground approximately 270 degrees around the rover. Collected samples will be deposited into a collection bay directly between the front suspension arms.

III. Technical Project Description

A. On-board Electronics

The core of the on-board computing system is the Supermicro A1SRI-2558F, a mini-ITX motherboard with a built in quad-core Intel Atom C2558 System on Chip (SoC). This motherboard was selected due to it providing a total of four USB 3.0 ports and two USB 2.0 ports. A Samsung 850 EVO 250 GB SATA III Solid State Drive with up to 540 MB/s read and 520 MB/s write speed is used. Additionally, two sticks of Kingston Technology 8 GB 1600 MHz DDR3L RAM are installed on the motherboard. Since nearly all computation and processing will be done on the motherboard, these components were selected for their speed and reliability. To control the motors and servos, an ATmega328P chip is connected to an Adafruit 16-Channel 12-bit PWM/Servo breakout board with I2C interface. The breakout boards PWM output pins are connected to Pololu Simple single channel and Robo Claw dual channel motor controllers.

B. Electronics Selection and Alternatives

When considering the central onboard processing computer, we looked at two potential solutions: the BeagleBone Black or a traditional motherboard. The BeagleBone Black is advantageous in its low-cost of $55.00 [1] and small form factor. However, it was deemed insufficient for multiple reasons: there are only two USB ports, the processor only supports single-threading, and the CPU and RAM is not fast enough for all the onboard calculations needed. After much research and comparison of traditional motherboards, the final selection was a Supermicro Mini ITX A1SRI-2558F. A mini ITX model motherboard was selected to keep the rover weight low and to fit in the chassis.

When considering the motor controllers the movement system, two options were viewed: direct control through Phidgets Advanced Servo 8-Motor 1061 controller or manually replicating the functionality of a motor controller by attaching a PWM expansion board to an ATMega328P microcontroller and attach PWM-controlled motor controllers to this unit. The design choice essentially boils down to having a central node in this architecture (that is, the microcontroller) for the motor controller components or have the motherboard control said components directly. The final decision was to incorporate a central hub for control. Adding a microcontroller resulted in additional overhead in the system, but introduces a level of abstraction. The onboard computer will only handle the communication of sending the operator's command to the microcontroller, and the microcontroller will handle generation of PWM signals to the motor controllers. In addition, Phidgets were hard to work with due to their lack of documentation and difficulty of use. They were designed to be used with a Windows operating system, which adequate drivers and software exist. Our system runs the Linux operating system, and it was a difficult and tedious process to compile the libraries for Phidgets.

C. Movement

Seven powered wheels provide motion for the rover. Steering is achieved through a combination of 3 mechanism: steering servos on the front two and rear wheels, modulation of the power applied to the differently sized wheels to maintain a uniform speed, and modulation of the power to each motor channel based on the turning radius. This allows nimble and smooth control of the rover, and even provides the ability to turn within itself in a differential manner.

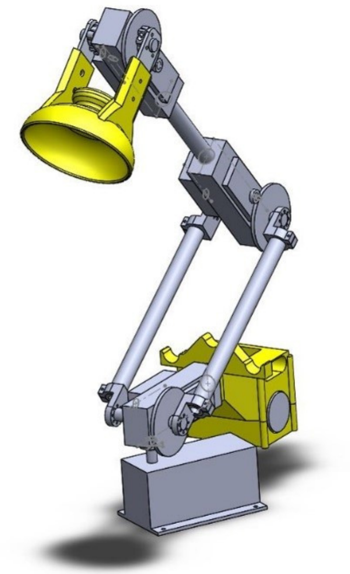

Fig. 2. 3D model of the arm and manipulator

A custom, 5-channel motor-controller was designed and a printed circuit board (PCB) fabricated in order to achieve individual control over all seven DC motors. Throughout testing however, it was found that the microcontroller onboard the PCB tended to reset at random when the motors were at full speed. Unfortunately, the issue remains unresolved due to time constraints to appropriately prepare for the competition. Instead, it was decided that commercially available motor controllers would be used for the rovers drive systems. On board each rover, there are two two-channel Pololu motor controllers and one one-channel, which are used to drive the seven DC motors on five channels. These motor controllers allow bi-directional speed control over each DC motor while also allowing an adjustable maximum acceleration and deceleration to limit the amount of mechanical and electrical stress on the system. The motor controllers signal is produced by 5 channels from a dedicated PWM servo control board, which interfaces with an ATMega328P microcontroller.

D. Sample Acquisition

Both rovers utilize a claw-style gripper. Each rover features the same arm, an off-the-shelf four-degree-of-freedom arm kit from Servo City. The claw gripper adds two additional degrees of freedom, however, with wrist rotation about the forearm axis and a degree of freedom to open and close the claw; however, there are only two points of contact between the claw and the specimens, making objects trickier to pick up. To compensate for this, the arm has been made analogous to a human arm, with five total degrees of freedom in addition to opening and closing of the claw. Each degree of freedom operates in a single plane, with the following ranges of motion:

1) First servo (shoulder rotation about base): full rotation parallel with rover chassis
2) Second servo (shoulder extension): 180° to 250° (between cradle and point of contact with chassis)
3) Third servo (elbow extension): 360°
4) Fourth servo (wrist extension): 190°
5) Fifth servo (wrist rotation. specific to the claw gripper): 360°about the forearm axis
6) Sixth servo (claw manipulation): fully opens and closes claw (servo rotation of 90°; claw opening is 2.8 in wide when fully open)

The arm has an extended radius of 60 cm. The granular gripper makes full use of this, with a collection radius of 60 cm from the center of the arms base. The claw gripper, with addition length due to the rotating wrist, has a collection radius of 80 cm. Both rovers have a camera directed at the gripper for sample acquisition.

E. Movement and Acquisition Controls

The rovers are controlled by the Robot Operating System (ROS), a communication framework for distributed robotics programs. ROS allows the rapid implementation of prewritten and custom programs, called "nodes." ROS nodes are able to communicate with other nodes and to external applications through communicational channels called "topics." Messages through ROS topics can range from formatted text to images [2]. ROS nodes in each rovers software framework will handle everything from actuating the servos and motors to processing the image data and creating a 3-D map of the environment.

The arm and drive control systems are comprised of 5 ROS nodes in total, 3 of which are shared between the two systems. These 3 common nodes are the command receiver node running on an ATMega328p microcontroller chip onboard each rover, the command parser node whose role is to receive and parse user input at mission control, and the translator node which serves as the interface between the parser and receiver nodes and also runs at mission control. There are two supplementary nodes which serve to read user input from physical devices and relay this input to the aforementioned command parser node: the ROS keyboard, and the ROS joy node.

The next node in the chain (the command parser node) is responsible for intercepting and parsing input from the keyboard and joy nodes. This node was written in order to keep track of the current servo angles and motor speeds for each rover, and calculate new angles and speeds from the input it receives. Once input has been parsed and the new rover settings have been calculated, this new data is sent over a rostopic to the command translator node.

The command translator node is responsible for generating PWM values for the angles and speeds it receives. The calculations performed in this node required many hours of calibration adjusting values in code in order to correctly transform angles and speeds into raw PWM data. Each different servo and motor model type required its own calibration, and gear ratios and wheel diameters were required from the Mechanical Engineering team members in order to correctly approximate these values.

The final node in the system is the command receiver node, running on the microcontroller chip onboard each rover. This chip accomplishes the simple task of generating (with the help of the I2C PWM breakout board) a physical PWM signal, replicating the PWM data received from the command translation node. This signal is then sent to the servo motors and motor controller boards, driving the rover and operating the arm.

The team encountered issues with the limited RAM and computational power of the ATMega238p microcontrollers. While the onboard microcontroller was originally responsible for translating angles to PWM data, this produced dangerous and unpredictable stack overflow errors. It quickly became obvious that optimization alone would not resolve this issue, and that the only solution was to either purchase more powerful hardware, or to lighten the calculation load on the ATMega238p chip. The team opted to use the cost effective solution, which was to delegate the job of command translation to a command translation node.

To provide easier arm manipulation for mission control operators, an automatic arm-relocation system was developed. Since the arm contains six degrees of freedom, it is a difficult task to operate the arm, and even more difficult to return a collected sample to the collection bucket. The automatic relocation system was developed so that operators need only to worry about retrieving the rock, and the arm is able to reset with one button.

F. Sensor System

An interface was designed to transmit the various onboard sensor readings to ROS. Initially, a single ATMega328P microcontroller was used to process control commands and transmit sensor readings. However, issues with processing delay resulted in adding a separate, dedicated ATMega328P to handle sensor transmissions.

Two types of sensors, not including the cameras, are used: an Adafruit 10 Degrees of Freedom Inertial Measurement Unit (IMU) with gyroscope and accelerometer, and an Adafruit 66 channel GPS unit with 10 Hz updates. The IMU provides three axes of accelerometer data, three axes of gyroscopic, three axes of magnetic/compass, barometric pressure, and temperature. Not only are these measurements transmitted to mission control directly, but they are also used in the calculations for motion planning algorithms of the arm.

The two types of sensors both communicate with the ATMega328P microprocessor through I2C. Each sensor is granted a dedicated ROS topic for the transmission of its data to the motherboard ROS node. The operators are able to view a formatted version of the data reported by each sensor on the mission control machine. Additionally, these two sensors are used for important autonomous functions of the rover.

The IMU is used for a crash-detection system. When extensive shaking is reported by the IMU gyroscope or an excessive change in the rover's spatial acceleration reported by the IMU accelerometer, the microprocessor sends an emergency broadcast message to the motherboard with the highest priority (similar to an interrupt). The motherboard then sends messages to the rest of the ROS nodes to immediately stop all motor functions, and prompt the rover operator with a potential crash detection. The rover operator must verify with an acknowledged command before the rover can regain motor functions. This system is implemented to prevent the rover from moving in the case of an emergency crash.

The IR sensor, mounted on the rover's robotic arm, is used for obstacle detection. The rover cannot traverse obstacles over the height of 0.5 meters, which is where the IR sensor is placed on the arm. If the IR sensor detects an obstacle within fifteen centimeters, the microprocessor sends an emergency broadcast message similar exactly like the crash-detection system. Again, the operator will need to verify with an acknowledged command before the rover can drive forward. This sensor is currently only implemented for objects in front of the rover.

G. Camera System

Providing vision for each rover are a pair of Genius 120 degree wide-angle cameras installed on a deployable camera mast. The mast will deploy at competition start by a spring and magnet to a height of approximately 75 cm from the ground. The camera pair is mounted on a slip ring and can thus be panned continuously by a continuous-rotation servo housed in the mast.

The wide view of these cameras allowed the forgoing of any pitch mechanism, as the rover chassis up to and beyond the horizon are visible at a pitch angle of 15 degrees. Furthermore, the wide field of view and narrow aperture of these webcams provide a depth of field from the rover chassis out to infinity.

Not only will these webcams provide a live stream to the operators, they will also be used in tandem to compute a real-time point cloud visualization based on the stereo-vision algorithms available in OpenCV. This point cloud will be sent into rviz, a ROS package, to provide an interactive 3-D representation of the current environment on the rock-yard to the operators. Additionally, this data can be used to match objects and build an evolving and persistent map of the rockyard to provide pathing assistance.

Finally, a narrower camera resides on the robotic arm, aimed directly down its length at the gripper, which will provide a direct view of the gripper and the sample to be acquired.

IV. TESTING

To measure the rover's speed, we created a track that is exactly one meter is horizontal length and use a tenth-of-a-second precision timer to determine time elapsed. The rover's front wheels are placed on the starting line, and the rover is driven across the one meter track at variable speed levels. When the rover's front wheels cross the finish line, the timer is stopped and time recorded. With each speed level, the measurement is repeated four times to ensure precision. Results from the four runs are averaged and reported below:

- Speed Level 0: 0.00 m/s (neutral/minimum drive)
- Speed Level 1: 0.14 m/s
- Speed Level 2: 0.28 m/s
- Speed Level 3: 0.42 m/s
- Speed Level 4: 0.56 m/s (maximum drive)

TABLE I. USE CASES AND TESTING FOR DRIVE SYSTEM

Key Press	Expected Outcome	Actual Outcome
Driving Base Case	Neutral (Speed 0)	Neutral (Speed 0)
w	Forward Drive (Speed 1)	Forward Drive (Speed 1)
w-w	Forward Drive (Speed 2)	Forward Drive (Speed 2)
w-w-w	Forward Drive (Speed 3)	Forward Drive (Speed 3)
w-w-w-w	Forward Drive (Speed 4)	Forward Drive (Speed 4)
w-w-w-w-w	Forward Drive (Speed 4)	Forward Drive (Speed 4)
w-w-w-w-s	Forward Drive (Speed 3)	Forward Drive (Speed 3)
s	Reverse Drive (Speed 1)	Reverse Drive (Speed 1)
s-s	Reverse Drive (Speed 2)	Reverse Drive (Speed 2)
s-s-s	Reverse Drive (Speed 3)	Reverse Drive (Speed 3)
s-s-s-s	Reverse Drive (Speed 4)	Reverse Drive (Speed 4)
s-s-s-s-s	Reverse Drive (Speed 4)	Reverse Drive (Speed 4)
s-s-s-s-w	Reverse Drive (Speed 3)	Reverse Drive (Speed 3)
s-s-w-w	Neutral (Speed 0)	Neutral (Speed 0)
w-w-w-w-x	Neutral (Speed 0)	Neutral (Speed 0)
s-s-s-s-x	Neutral (Speed 0)	Neutral (Speed 0)
Steering Base Case	90° Steer (Forward)	90° Steer (Forward)
a	60° Steer	60° Steer
a-a	30° Steer	30° Steer
a-a-a	0° Steer (Direct Left)	0° Steer (Direct Left)
d	120° Steer	120° Steer
d-d	150° Steer	150° Steer
d-d-d	180° Steer (Direct Right)	180° Steer (Direct Right)
a-d	90° Steer (Forward)	90° Steer (Forward)
a-a-a-z	90° Steer (Forward)	90° Steer (Forward)
d-d-d-z	90° Steer (Forward)	90° Steer (Forward)

It should be noted that once the motors are at maximum drive, any additional commands to increase speed will be ignored, and the rover will maintain its maximum speed. The same principle follows suit for the steering servos, any additional commands to extend servos beyond their range of operation will be ignored, and the rover will maintain its current steering position.

Testing for the control system was done using keyboard control. When the key is pressed, the resulting response from the rover is observed and recorded. The testing use cases and results are listed in Table 1. The Key Press column denotes the sequence in which the keys are pressed. For reference, the keyboard controls are: w-increase forward drive; s-increase backward drive; x-reset motors; a-steer left; d-steer right; z-reset steering. The result from testing the use cases was a working prototype that satisfied all testing requirements.

Testing of the arm control system was done by extending each of the servo components to its maximum and minimum values. Due to the arm and gripper having a combined total of six degrees of freedom and the different angle limits for each servo, documentation of every possible combination will take several pages with thousands of rows. Due to its unviability, the table has been omitted from this report. However, successful operation of the arm has been observed during lab demonstrations and presentations.

The sensory system was tested using specifically designed scenarios. For the IMU component, a crash test was simulated by placing the rover on variable height platforms and driving the rover off the platform to simulate crashing. The platform was constructed using blocks with a uniform height of 0.2 meters. The initial platform used a single block (i.e. the rover is 0.2 meters above the ground), and the crash detection system did not stop the motors when the rover drove off the platform. This result is as expected, it is possible for the rover to experience minimal shaking while driving over uneven ground. Two blocks were then used for a combined height of 0.4 meters, and the crash system did stop all motors after driving over. The experiment was repeated with three blocks at 0.6 meters, and the system was still observed to stop all motors. The result of this testing satisfies the expectations set forth.

For the IR component, obstacles of various colors and shapes were used to block the IR sensor to prevent the rover from moving forward. The IR sensor successfully shut down motors for all obstacles tested, including: poster board, chair, wall, table leg, and a human hand covering the sensor.

The following list summarizes all other testing done on the rover, which satisfies the competition design constraints and requirements.

- Speed: The rovers at full speed on level ground clocked in at 0.56 m/s, or 1.25 mph.
- Weight: Each rover currently has a mass of 15.40 kg, for a grand total of 30.80 kg.
- Size: Both rovers are 88 cm long and 50 cm wide, with a stowed height of 49.5 cm and a deployed height of 77.5 cm.
- Obstacles & Payload: Each rover has been documented driving through a variety of inclines and over obstacles 15 cm tall with a payload volume of 0.5 ft3 and enough torque to carry any amount of rocks that can fit therein.
- Operating Time: Maximum operating time with full draw and payload is 43 minutes.
- Drive Power: Maximum drive power of 420W was achieved with seven 12V DC motors.

V. Packaging

The rover's internals are housed in an Aluminum chassis, designed and created by Mechanical Engineering students in the team. The aluminum chassis is lightweight, and durable enough to sustain rolls and small falls. The chassis also has a removable cover, which grants easy access to the internal hardware. To prevent the Aluminum chassis from short-circuiting the internal electronic components, a piece of plastic was used as a barrier between the metal chassis and components.

To protect the servos' exposed wires on the outside of the chassis, braided wire sleeves were used to cover all external wires with the exception of the wires for the arm. Due to space constraints, there was no room to fit braided wire sleeves into the confines of the robotic arm.

To satisfy competition requirements of ability to operate in light rain, water-proof stripping were glued to the chassis' removable cover to prevent water damage to the internal electronics.

Fans are installed the rear of the rover to prevent the internal electronics from over-heating, since the weather in Houston could unpredictable. The chassis contains water-jet cutouts of the University of Wyoming Steamboat logo, which is used for fan ventilation and providing aesthetic value.

VI. Other Considerations

A. Project Cost

The total budget for this project is $12,250.00. Sources of funding were $10,000.00 grant from NASA and $2,250.00 grant from the Wyoming NASA Space Grant Consortium. The overall development, materials, and manufacturing cost for both rovers combined is $6,815.00. The control and sensory system cost totals to $1593.44 without factoring the servos and motors into account, which were previously purchased and donated to this project.

B. Social and Political

This project was conceived through the NASA Revolutionary Aerospace Systems Concepts - Academic Linkage program, a program to encourage designs from engineering students at the university level. Successful and unique designs may be taken into consideration for future NASA programs and projects.

C. Health and Safety

The chassis contains sharper corners and edges, which may pose incision hazards. The on-board battery is a lithium iron phosphate battery (LFP). Improper grounding and mishandling of electronic components may result in fatal electrical shock or explosion. Extreme care and caution is required to operate the internal components.

D. Aesthetics

As our team was representing the University of Wyoming at this prestigious competition, it was decided to use a water jet cutter to carve the University of Wyoming Steamboat logo into the sides of the rovers' chassis. We received approval from the university marketing to use the logo royalty-free, since it was not for commercial use.

A white coat of paint was applied to the rover for aesthetic purposes, but also the reflection of sunlight to reduce heat on the metal chassis.

E. Manufacturability

Due to the nature of the final product, it is NOT designed for the average consumer. This product should not be mass produced, but rather hand assembled carefully. After the on-board electronic components are ordered from distributors, they must be placed in the chassis and connected by hand. The arm and gripper are off-the-shelf products, and also requires hand assembly. This product is also difficult to transport when assembled. Transportation of the two assembled rovers from Laramie, WY to Houston, TX required half of a full-size suburban vehicle. The software components of the system can be reproduced easily. The mother-board's hard-drive can come preloaded with the Operating System and code downloaded from our online repository. The microprocessor can be pre-programmed before delivery.

F. Sustainability

The on-board electronics in this project can all be reused. After dis-assembly, the central motherboard and attached components can be reused in a desktop computer. The microprocessor, motor controllers, and sensors can be reused for other robotics projects. The cameras can be detached and used as webcams with any computer through USB. However, the chassis and robotic arm are Aluminum and specifically designed for this project, so they must be recycled.

G. Governing Standards

The United States Department of Labor, Occupational Safety and Health Administration (OSHA) provides the governing standards for robotics under 29 CFR 1910 [3]. Due to the autonomous functions this rover can perform, it is classified as a Level 2 autonomous vehicle (Partial Automation) by the Society of Automotive Engineers [4], and subject to government regulation.

VII. Lessons Learned

My primary take-away from this project is teamwork in an interdisciplinary field. In this project, students from Mechanical Engineering, Computer Science, and Electrical Engineering came together to design a working prototype. The students were primarily experts in their individual fields, so good communication skills are required when communicating with an interdisciplinary team. In addition, project time-lines and calendars are crucial to ensure all participants are staying on schedule, it can also come in handy as a stress-reducer. Funding is also an important aspect for a large-scale project. Thankfully for the grant NASA provided, we were able to bring our design to life.

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[3] *Occupational Safety and Health Standards*, Regulation Part 1910, United States Department of Labor, Washington, DC.

[4] *Society of Automotive Engineers*, New SAE International Standard J3016, SAE International, Warrendale, Pennsylvania.

Appendix A
Parts List and Cost Analysis

- 2x Supermicro Mini ITX Motherboard, $545.90
- 2x Samsung 120GB Solid-State Drive, $133.96
- 4x Kingston 8GB DDR3 RAM, $231.96
- 6x Pololu Infrared Proximity Sensors, $35.70
- 2x ATMega328P Microprocessor, $7.40
- 2x Adafruit 16-Channel PWM/Servo Shield, $35.00
- 2x Adafruit 10-DOF Inertial Measurement Unit, $59.90
- 4x Genius 120-degree Wide Angle Cameras, $139.92
- 2x Microsoft LifeCam 720p Webcam, $60.00
- 4x RoboClaw 2x7A Motor Controller $279.80
- 2x Pololu Simple Motor Controller $63.90
- Servos and motors were previously purchased by others and donated to this project.