University of Arizona

Exploratory Space Vehicle (XSV)

Final Report for

RASC-AL ROBO-OPS Competition

The Team

Affiliated Institution: The University of Arizona

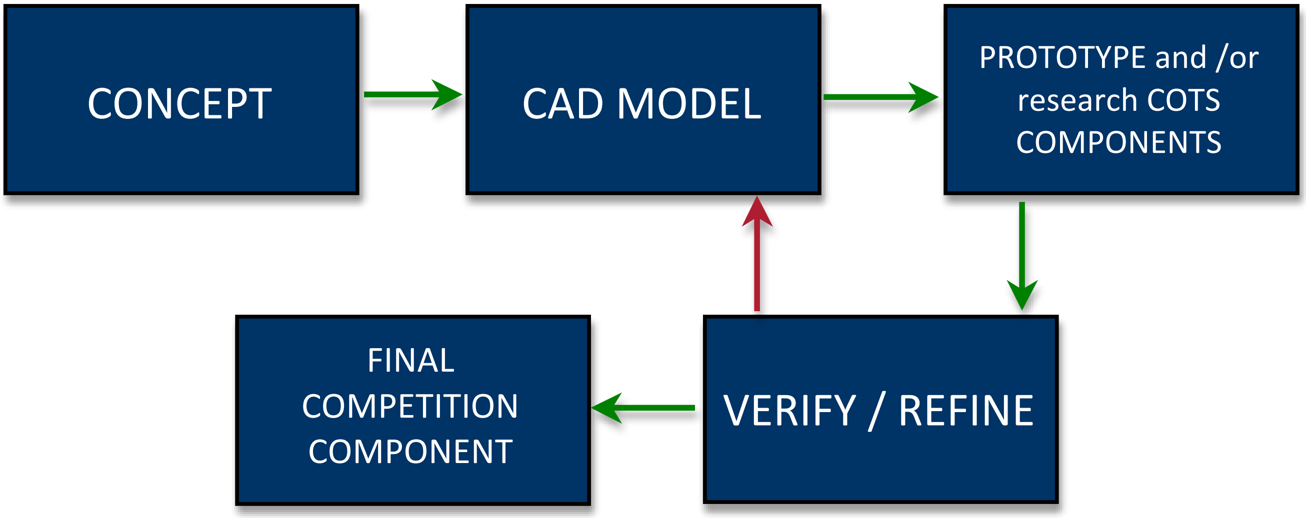
Advisors: Jeremy Fergason, Ara Arabyan & Angel Crespo

Team Leader: Jordan Odle

Team Members: Aaron Petras, Brandon Pitts, Daniel Papajohn,
Jesse Odle, Lane Ellwood

Design, Fabrication & Testing

The design, fabrication & testing for the XSV was focused around producing a capable yet simple rover that met or exceeded the design requirements, as well as a few self-imposed requirements. The general process that we followed is illustrated in the process diagram below.



This process was applied to each main subsystem over the course of the project, and the individual systems will be detailed later. Each application of the process to the various subsystems carried its own nuances and variations tailored to the system. In general the project started from the initial call for proposals, where our team tackled the concept of the XSV. The concept took on several variations, and much discussion was poured into determining the final XSV Concept. This is the concept that was put forth in the proposal, and accepted into the competition. From there the process of designing for a production model started. This comprised of revisiting every aspect of the XSV and the individual subsystems, adding in the fine details and doing analysis on different elements of the rover. From there either prototypes were fabricated for verification, or research was conducted into commercial off the shelf components (COTS). Often times the design required modification or small refinements before being finalized. After this stage the final component for use on the competition rover was fabricated, or if the component was a COTS then it was purchased.

The overall philosophy for the design and fabrication of the XSV was to define a sub-frame that would then have each subsystem mounted to it. This allowed the simultaneous design of each subsystem to be carried out semi-independently by different members of the team. And the final solution would have the sub-frame with each “bolt-on-ready” subsystem mounted. This approach required a fairly static sub-frame design, and each subsystem to have little interference between the other systems. This worked very well throughout the project, however in some instances each subsystem was not entirely independent.

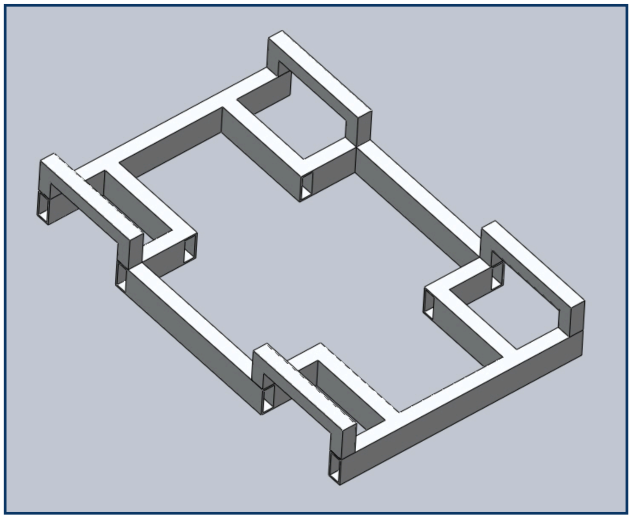
The subsystems that will be addressed are as follows:

- Sub-frame
- Arm and Tool Assembly
- Suspension
- Drivetrain
- Camera Boom
- Command and Control
- Electronics Package

Sub-frame

The competition calls for a rover that is capable of traversing a wide variety of challenging terrain, collecting and storing rock specimens, and being tele-operated. The vehicle, with which this objective will be accomplished, needs to have these ruggedized mechanical properties. One of the core elements to this is a solid mechanical structure that can take on the abuse from the environment. For the XSV, this comes in the form of a sub-frame that is built to handle adverse and variable loads transferred from the suspension, as well as provide a solid platform for the other subsystems.

The sub-frame was designed as the static element that every other subsystem would be designed around. Due to this approach, the design was kept as simple as possible and underwent few design changes throughout the project life. The driving requirements that influenced the design were the maximum stowed dimensions and maximum weight. From this, the rough sub-frame dimensions were designed and material selected. Due to the significance of weight in a space mission, the decision was made to not design for the max weight but target a much lower weight. This drove the decision to make extensive use of aluminum and engineered plastics in the fabrication of the XSV. The sub-frame was no exception, especially being that it constitutes a significant percentage of the total weight. Due to the rugged application, the XSV uses oversized 2 inch by 1 inch extruded aluminum tubing joined together with strong but lightweight welds. This provides exceptional rigidity to dynamic loads, and a solid support structure for the XSV. The only prominent design feature that was designed in anticipation of another subsystem was the suspension support structure. This was also designed very generically, and the suspension subsystem was then designed to integrate into the sub-frame. A CAD model of the sub-frame is shown on the right. Here you can see the aluminum tubing construction, as well as the suspension support structure.



Arm and Tool Assembly

The XSV contains a fairly simple arm and tool mechanism that will allow the team to easily complete its objective of grabbing and storing target rocks. The main goal when designing the tool mechanism was to maintain enough grip on the rock specimens so they would not fall while attempting to place them in the storage bay. Therefore, when the arm was designed, it was such that enough torque would be available to provide sufficient grip to the tool mechanism by means of a pull system. It was also designed to provide ample torque to rotate the different sections of the arm with the presence of the rock load. The following sections will describe the design and manufacturing processes of first the tool mechanism and secondly, the arm mechanism.

Tool Mechanism

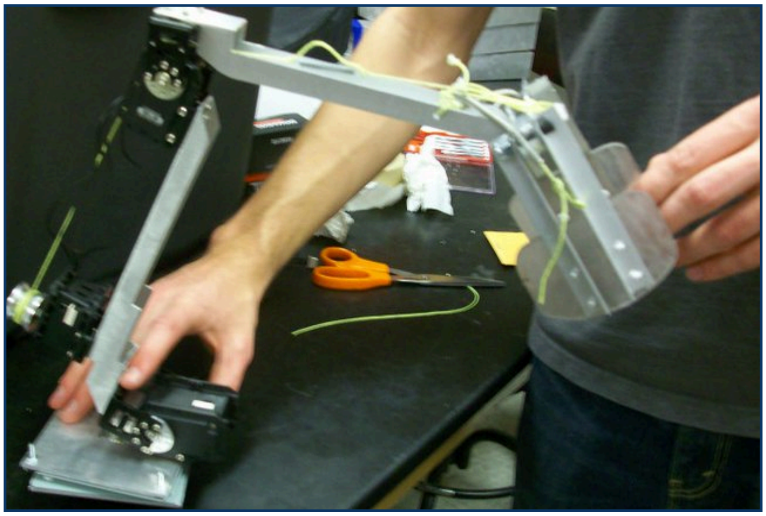
Design

When brainstorming the design of our tool mechanism, the team came up with three different designs. One was that of a claw-type mechanism, the second was of a scoop-type mechanism and another was a clamp-type mechanism. The main goal of the tool mechanism is to provide a significant amount of grip on the rock specimen and also to allow the controller some margin for error when attempting to grab the rock sample. A claw mechanism would provide enough grip if foam or rubber would be placed on the tips, however, the controller would have to be very accurate when attempting to grab the target rock sample. A variant of the claw design that was also considered was a claw-scoop hybrid, in which the claw, when in its closed position, will completely enclose the rock sample. This would allow the controller more room for error and would also ensure the rock sample would not drop while placing it into the storage bay. This variant, however, would scoop up not only the rock, but also any sand or debris that may be surrounding the rock. Another consideration was to use a scoop or shovel-type mechanism for the tool. This would be similar to the scoop on the front of a bulldozer. This design would be much like the claw-scoop hybrid design in which it would allow more room for error; however, it would also scoop up unwanted materials from the environment. The last concept design was a clamp-like tool that would consist of to plates that would clamp down on the rock sample. If foam or rubber were added to the two plates, this design would give significantly more grip than the claw-type design. This design would also allow the controller much more inaccuracy when attempting to grab the rock because the rock could be clamped anywhere between the two plates and still receive enough traction due to the foam or rubber. This clamp-type design would also avoid grabbing any unwanted materials. Therefore, this design was the one that was chosen for our tool mechanism. A SolidWorks model was drafted and the sizing of the tool was determined based on the given size range of the rock samples that the tool would need to grab.

Manufacturing/Prototyping

The manufacturing process began with the selection of material that would be used for the tool mechanism. The first prototype that was constructed was made from aluminum L-bar with a dense plastic clamp. The aluminum was used for a bracket to attach the clamp to the arm itself. Rivets held the aluminum together and the clamp was then attached to the bracket with two pins. Two tension springs were mounted on the tool mechanism to keep the clamp open and a drawstring attached to a pulling mechanism (described in the arm mechanism section) on the arm was used to close the clamp. This first prototype provided us enough information to confirm that this design would work for our objectives and met our goals for the tool mechanism. However, as we tested the tool more and more by drawing in the string with our hands to pick up random objects, the string broke and left the tool useless. The tensions springs were also mounted in a way such that they would get caught on the arm and not return the clamp to its opened position. This was clearly a defect in the design and would not work for the competition.

In the second prototype, the string was replaced with a 1/32 inch steel aircraft cable, which proved to be reliable and would not break under tensile loading. The overall design of the tool was also altered so that the tolerances would be tightened and so that the springs would not hinder the operation of the clamp. Because the tension springs in the previous prototype were not performing up to the team's expectations, it was decided that torsion springs would be better suited to the application. The SolidWorks design was then altered to implement torsion springs and also to tighten the tolerances of the tool mechanism. It was also decided, in order to increase the tolerance of the tool, that a selective laser sintering (SLS) process would be used to construct the tool with a nylon-based material. Once this prototype was manufactured, testing began and it proved to be a reliable design. The grip force was enough to move the rock samples from the ground to the storage bay without them dropping from the clamp. Additionally, there were no problems with the precision of grasping target rocks.



Arm Mechanism

Design

The various arm mechanisms that were first designed all contained a system of two pieces connected by joints, similar to the human arm. The arm includes a servo operated joint at its base, where it mounts to a rotation plate. The rotation plate is supported by steel bearings and driven by a servo which is mounted underneath. This allows the arm to rotate enough for the tool to pick up a rock sample and deposit it into the onboard storage. One design made use of a chute that would have an opening between the clamps of the tool mechanism and would run down the arm, into the storage bay. After further thought on this design, the team decided there were some reliability issues with the rocks getting stuck within the chute and therefore this design was scrapped.

There were two initial designs for the pulling mechanism that provides the clamp with enough force to hold the rock samples. One design used a lead screw mounted on the forearm of the rover that would draw in the cable attached to the clamp. This lead screw would be wound by a servo mounted on the arm. The other design involved a spool attached to a servo, in which the cable would be attached and wound around. This design was chosen because it was a lighter weight design and much easier to manufacture and implement into the overall design of the rover. An initial design also called for two servos to be mounted at each joint of the arm, but after a force analysis, the increased torque from the extra servo at each joint was deemed unnecessary and also added weight to the design. Therefore, the final design contains only one servo mounted at each joint.

Manufacturing/Prototyping

The prototype for the arm mechanism is machined from 1 inch by 1 inch aluminum tubing that has been cut in half down its length to reduce its weight. Mounting brackets for the servo connects the two pieces of the arm and also hold the servo onto the joint of the arm. The clamp is mounted to the arm by means of a bracket as well. The other end of the arm is mounted on another servo that will act at the base of the arm. This servo is connected to the rotation plate that will allow the arm to rotate. The rotation of the plate is driven by another servo that is mounted underneath it and the plate itself is mounted to the sub-frame of the entire rover. Towards the base of the arm, another servo holds the spool that will draw the aircraft cable in and out to operate the clamp mechanism.

Testing of this prototype consisted of running the servos to test whether or not they would be able to rotate and bend the arm without difficulty. The test also involved determining if the pull system provided enough force to the clamp to grab rock samples. After testing, it was concluded that this prototype met the requirements that the team had initially set and therefore no further alterations were required.

Suspension

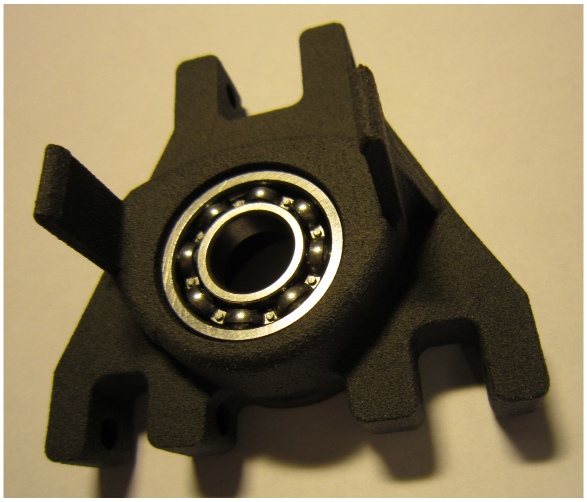
One of the main functional design requirements for the rover is the ability to traverse a variety of terrain, high-grade slopes, and obstacles. To meet this requirement effectively, the XSV employs a four wheel independent suspension system. This will ensure a more efficient and sure footing by the XSV throughout the mission.

Design

When the design for the suspension system was approached there were several challenges that needed to be addressed. The wheels needed to be mounted in such a way that their orientation is constantly controlled, and so that the load from the chassis is transferred to the wheel effectively. Our solution to this was a wheel hub that captures a shaft by two bearings, this allows radial and axial load to be transferred from the hub to the wheel. The challenge is then to mate the motor to the shaft, which is addressed in the drivetrain section, and to transfer the load from the XSV out to the wheels. This is addressed through a few components; the XSV design called for equal length upper and lower control arms as well as a single coil spring per wheel. This is very similar to the design used in racecars, and ruggedized baja vehicles alike, for its ability to provide good stability and control in extreme environments. The control arms transfer lateral loads to the wheel hub, while the spring transfers vertical loads to the wheels. The key to using a spring-loaded suspension system is that it allows more even and constant distribution of the weight over uneven terrain. This improves traction and control, as well as effective power available for drive. The requirement to traverse high-grade slopes, and challenging terrain make this capability and subsystem especially critical to the XSV mission.

Fabrication

The fabrication of these complicated components turned out to be far more challenging then the system design. Our limited access to CNC's capable of machining high strength aluminum, required multiple iterations of the design in order to adapt to the resources available. The final components used nylon based SLS parts for the hub and control arms, while the brackets with which they are mounted to the XSV and the spring mounting brackets still call for the



higher strength aluminum. Due to the use of SLS parts, the final part designs required features that account for the reduced strength from the NyTek material. An image of the final wheel hub is included; some of the features that are visible include the bearing cavities, control arm mounts, and servo mounting clips which project out from the hub.

Drivetrain

Scope of Work

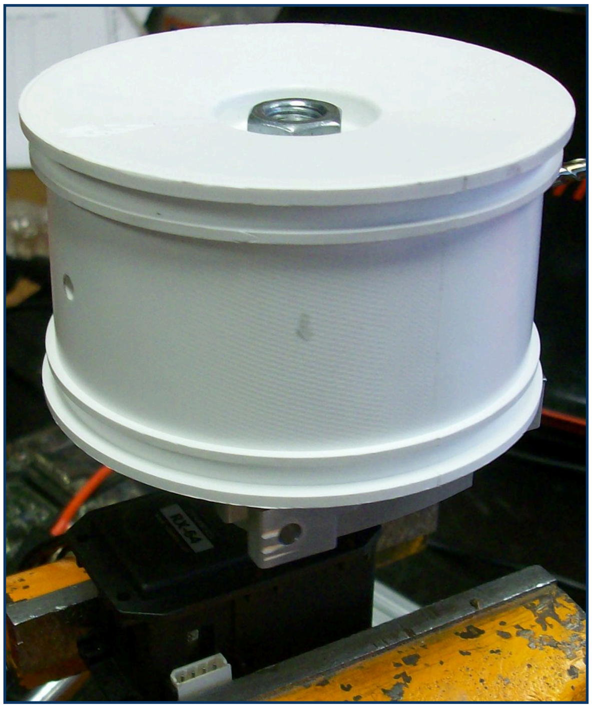
The drivetrain is the system within the XSV that will generate power and deliver it to the ground. The competition requirements state that the rover must be capable of traversing sand and negotiating high grade slopes, which is accomplished by the drivetrain design implemented on the XSV.

Steering System

The team began the process of developing a drivetrain by first establishing the steering system. The three prominent concepts were; car steering, tank drive, and swerve drive. Car steering would be a system, in which the two front wheels turn to guide the robot in a specific direction. Car steering was the least desired system because of the inherent complexity and large turning radius. Tank drive is a steering system that changes the rovers orientation and direction by driving the wheels at different rates per respective side. Tank drive is a very appealing system because the robot can achieve zero radius turns and is a simple system to design and implement mechanically. Swerve drive also requires control of each wheel, thus providing the most maneuverability. Each wheel can turn 360 degrees, allowing the rover to move in any direction with out the need to change orientation. However, swerve drive is a larger and more complex unit than the other systems. This would require a significant amount of programming and fabrication time. Tank drive was the steering system of choice because it was the most attainable within the time constraint of the project. It is a lightweight and compact system, which is essential to the rover achieving an overall weight under the 45 kg. maximum weight requirement.

Motor, Shaft, and Hub Assembly

The motor, shaft, and hub changed drastically throughout the design and fabrication phases largely because each one of these units is dependent on the other. The original concept in our project proposal used CIM motors to drive the wheels. These CIM motors would be mounted onto the rover’s chassis, and delivered power over a shaft. Since the rover will be traveling over rugged terrain we designed a suspension system to keep the rover stable. To accommodate for suspension travel we created a drive shaft that had two Cardan joints, which allow continuous torque to be applied throughout the designed travel. Before starting the fabrication of the drivetrain we completely modified these units because, through analysis, we discovered the Cardan joints were causing uneven rotation in the shafts that translated to uneven rotation in the wheels. To resolve this issue, a lighter more compact high torque servo was chosen that could be directly mounted on the hub. This modification would remove the issue of the double Cardan joints and it would reduce the weight of the robot, thus achieving a lower overall weight. Since the servos come with an array of embedded sensors and a speed controller, it made programming the drive system much simpler. In addition, it provides a much more durable and reliable unit. To integrate the servos into the rover, the wheel hubs were altered so that the servos mounted directly to the hub. These revisions took place over a long prototyping phase, which included creating multiple CNC models. The final part was created using an SLS process much like other components.



Battery

The switch from a large motor to a small servo reduced the required battery power supply. Power supplies are often high density, which results in a significant amount of weight. When less power is required, smaller sources are required, which will help reduced the XSV's overall weight.

Camera Boom

The camera boom is a relatively simple component. This component's primary function is to bring a camera from its stowed configuration to a position from which the rover's front half can be seen as well as what lies ahead of it. Once the camera boom is deployed the controller will use this camera angle as a primary means of planning the XSV's path.

Component Design/ Development

The simplicity of the camera boom's design is that it is meant to be deployed only once; after deployment it is kept in the upright position. The initial design concept changed very little from the beginning in that it was intended to fold downwards over the top of the rover in order to meet the maximum stowed height requirement of half a meter. The camera boom shown in the project plan proposal is mounted towards the back and centered in the middle of the frame. The boom itself was to be an aluminum bar/rod that would rotate about a pin joint anchored to the rear of the frame. It was to be powered by a gas spring, which would be compressed when the boom was manually folded into the stowed position and held in place by a removable pin that would pass through the boom. The spring was to be mounted towards the bottom of the boom, near the rotating point, in order to allow the beam to deploy sufficiently at the spring's maximum extended state. An actuator was to be used for triggering the pin release, and the gas spring would then push the boom into the deployed position with the pin removed.

As final development of the boom was in progress, both gas and conventional springs were considered for powering the component, as well as electric linear actuators. The decision was made to ultimately go with a gas spring in order to reduce the number of sub-components that would need to be manufactured/ purchased for a conventional spring. The linear actuator, while capable of both extending and retracting the boom on its own, was deemed unnecessary as team members saw no need for the boom to be re-stowed. An additional electrical actuator would also have added complexity to the control scheme. However, before a spring was to be purchased, geometry and spring strength needed to be specified. Being that the rest of the XSV body was already close to the maximum stowed dimensions in its fully deployed configuration, the boom did not need to be stowed to a perfectly horizontal position, however it would need to be mounted off-center so as not to conflict with the storage bay.

A gas spring capable of producing 20 lbs force and a maximum extension of 3 inches was selected. One end is anchored to the sub-frame, while the other end is mounted a few inches from the pin joint on the camera boom. These mounting positions were determined such that the desired stowed and extended configurations were met. The boom itself was machined from 1 inch by 1 inch aluminum square tubing and mounted to the rear portion of the rover frame. When fully extended, the boom is about 15 degrees from the vertical making the maximum height of the entire rover approximately 28 inches. A webcam has been mounted at a downward angle at the top of the boom, making it possible for the controller to see the XSV as well as in front of it. When in the stowed position, the boom lies across the rock bay frame, and is held in place by a pin that runs through holes in the boom and two additional anchor points. To release the boom, the pin is attached to a cable, which is in turn connected to an RX-28 servo actuator mounted to the rover frame.

Command and Control

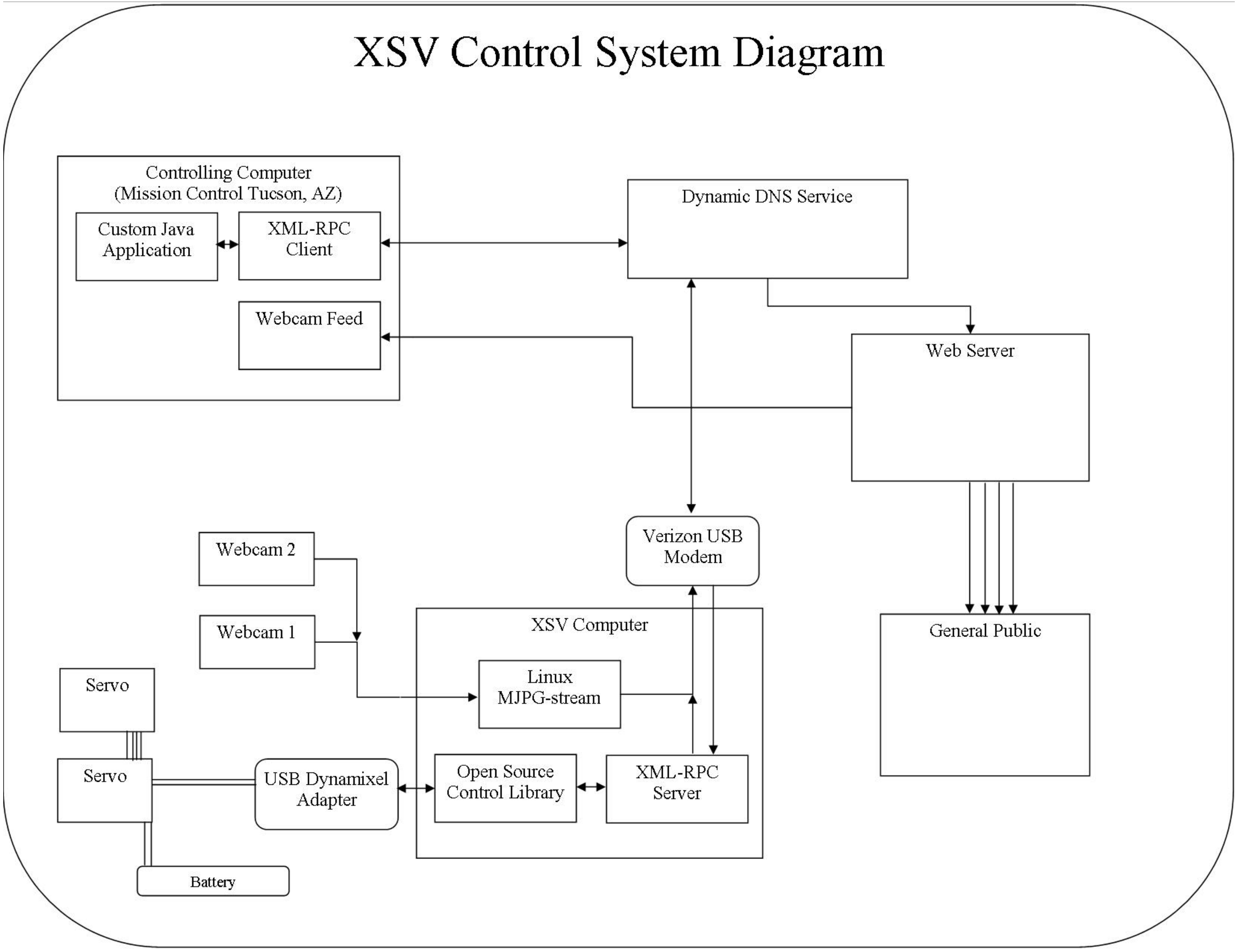
Control is an indispensible part of the XSV project. Although the XSV does not have any intelligence simulation, control is not trivial to implement. The requirements specified that the control must rely solely on data gathered from the XSV itself. This means that no communication between the two halves of the team would be allowed during competition, and the controlling personnel back at mission control in Tucson must rely on data delivered remotely by the XSV.

The location of the controlling team members was required to be the home campus of the team, in this case the University of Arizona in Tucson. This fact complicates rover control by eliminating control schemes such as radio transmitters as viable options. Essentially, control is limited to the Internet. In fact, it was specifically required that communication be channeled exclusively through a Verizon broadband card. This limitation is fairly restrictive because of the relatively small bandwidth that communication may be limited to depending on network conditions at the competition.

The control scheme chosen utilizes two webcams as data signals to the Tucson group, although only one may be made available to the general public to avoid running into the bandwidth ceiling. One camera is mounted on a boom above the robot, and one is mounted on the grasping arm to better view rock retrieval. The servos utilized in construction can also return a variety of information to the Tucson group if deemed necessary, such as heat, position, and torque.

Control signals to the robot will be sent via a custom Java application, and utilized XML-RPC as a transmission method through a dynamic DNS that will patch control to the XSV's IP address. The dynamic DNS is necessary since the XSV will not have the same IP address each time it starts, due to the use of Verizon broadband. On the XSV, a Toshiba netbook will run the XML-RPC server in Python. A Linux shell will also be run on the computer to facilitate use of a program called MJPG-streamer. Other web based streaming services were considered, but MJPG-streamer was selected for its low latency, eliminating the buffering found on the web services as a concern. The computer uses a Robotis USB2Dynamixel Adapter to communicate with the Robotis servos that drive the machine. An open source redistributable Python library developed at Georgia Tech Research Corporation called lib_robotis.py was used to direct communication between the computer, the adapter, and the servos.

MJPG-streamer will be streaming camera data only to a web server at Rincon Research Corporation, from which the control team, as well as the general public may view the feed. The website will have an administration interface that the team will be able to use to toggle from webcam to webcam, and a public interface which only allows viewing. The reason for limiting viewing to one feed at any time is the limited bandwidth that will be available.



Electronics Package

The original plan for the on-board computer was to use a Chumby Hacker Board. The board runs a simple Linux shell, which required a serial interface to be communicated with for programming. Eventually, it was decided that a netbook should be used instead. The main reason for the switch was the difficulty of setting up the Verizon card in the Linux shell. The netbook allowed the team to use the Windows software that Verizon provides for using the card. The netbook was also able to run a Linux shell for the MJPG-streamer software used for webcam streaming. Another feature of the netbook was that if the control software went down or failed to start during the competition, services like LogMeIn could be used to regain control integrity. This provided a safety net for any software failure other than loss of internet connection. Overall, the more powerful option of the netbook was a safer option than the welter-weight Chumby.

Selecting a Verizon broadband card was accomplished by calling Verizon support, who recommended the Novatel USB760 when the team mentioned their desire for Linux compatibility. Nevertheless, connecting to the Verizon network proved difficult in the Linux shell.

Webcams were selected by reviewing an online list of cameras compatibly with the UVC Linux Driver. Also, a high quality webcam was selected for the main camera (mounted on the boom above the XSV) so that the best quality that the limited broadband connection could support would be achievable by the camera. The final selection was the Microsoft LifeCam Cinema camera. That camera has a 720P maximum resolution, which was already far higher than the team expected to be able to stream. Even higher resolution models were on the list, which although available and within the budget, were not deemed necessary. The other camera did not need to be as high quality, and would serve only to view the end of the arm when retrieving rocks. For this role, the Logitech Webcam C200 was selected.

XSV Specifications and Capability Reference

Requirement	Requirement Value/Description	Final Design Target
Size	No larger than 1 m x 1 m x 0.5 m stowed	0.550 m x 0.866 m x 0.433 m
Weight	Less than 45 kg	~12 kg
Ground Clearance	10 cm	12.7 cm
Slope Negotiation	33% grade	Individual wheel motors (4) with 64 kgf-cm torque
Rock Size (for arm)	2 to 8 cm diameter	Clamp-style tool mechanism with foam padding
Rock Weight (for arm)	20 to 150 gm	28 kg-cm torque servos
Rock Transportation	Carry 5 rocks throughout course	Aluminum basket; 13 cm x 18 cm
Rock Identification	Distinguish Color of Rocks	Color Webcam
Terrain Traversing Capability	Sand, Grass, Small Rocks, Dirt	Individual wheel motors (4) with 50 kg-cm torque
Run Time	At most 1 hour	2+ hours with continuous operation
Power Plant	Cannot run on internal combustion engine	5.5 Ah Li-Polymer Batteries (2)
Weather	Must be operational in light rain	Internally stored electrical components

Public Outreach Activities

The team has been very involved, not only in the fabrication of the rover, but by also encouraging the community to play an important role in our project. By teaming up with the Sonoran Science Academy, we find students constantly asking questions and involving themselves with the fabrication of our rover. Because the Sonoran Science Academy is K-12 our rover project brings together all different ages and learning levels. This enables younger children the opportunity to get excited about robotics and engineering! We even had a fifth grader ask and have us show him how everything works in the robotics lab, from welding, machining, and even programming. Besides from playing an important role at the Sonoran Science Academy we have also found other ways to involve the community.

Internet sources such as Facebook and Youtube gives our team the opportunity to reach out to people in the community that do not frequent the Academy. By uploading photos and video footage people are able to ask questions and comment on our updated pages. People now find us to ask questions and to see how the rover project is coming along. The team also finds ways of putting our rover story in published material such as the Daily Wildcat, a student run campus newspaper. Our team has not finished the rover completely, but when completed we plan to hold demos and/or booths at a few different locations.

Mesa Verde High School, engineering day at the University of Arizona, and the Sonoran Science Academy will all be able to see the rover in action. They will be able to control the rover as well as see how it was designed and manufactured. By controlling the rover, they will be able to see the various functions of the XSV.

Outreaching is important for inspiration and the growth of our young community. By performing these outreach activities we hope to inspire the youth to become active in the field of engineering and robotics!