A Salamander-Inspired Robot for Traversal of Unknown Rough Terrain in Disaster-Response Scenarios

Revision 2

ECE 4012 Senior Design Project

Salamander Robot Team - Group LM2

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Executive Summary

Robots have the potential to serve as extensions of emergency-response professionals. During the immediate response to a disaster, rescue robots can provide valuable real-time data to help assess and monitor a situation and potentially save lives. In environments with hazardous materials or precarious structures, robots can navigate to places humans cannot.

However, large-scale catastrophes are often characterized by rough, uneven terrain that may result from rubble [1]. Rough, uneven terrain poses a challenge for traditional tracked (uses tracks/treads) or wheeled robots to traverse. One solution may be to increase the size of the tracks or wheels robot, but this poses logistical and cost issues.

We propose a salamander-inspired four-legged robotic platform that resolves these terrain-related challenges by virtue of the salamander's unique kinematic properties. Compared to legged and tracked robots, salamanders provide increased mobility (segmented legs, flexible spine), stability (low center of gravity), and portability (small size and weight). The proposed robot will build upon a biomimetic design [2] by optimizing the salamander's physical dimensions and gait parameters for good locomotion performance, even over rough terrain.

We hope to contribute to the field of disaster robotics by evaluating the utility of our bioinspired four-legged design for rough-terrain, and comparing it with other unmanned ground vehicle (UGV) options. We expect to ultimately demonstrate the salamander robot's ability to easily traverse terrain which is difficult for other types of robots. The total development costs for the proposed robot are \$154,394.46, which nets a 22.8% profit margin for a \$200,000.00 price point. The total parts cost is \$4,798.30.

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1. Introduction

The Salamander Robot Team will design a bionic salamander robot that will be able to handle the low-level joint control associated with traversing rough, uneven terrain. This capability be useful for disaster-response operations.

1.1 Objective

The team will design, build, and test a robotic salamander with a robust control system for movement over uneven landscapes such as rubble or potholes. The robot will be built with up to 30 degrees of freedom to accurately simulate the movement of an actual salamander. Figure 1 shows the servomotor layout for a current state-of-the-art biomimetic salamander robot, named Pleurobot.

1.2 Motivation

A subset of the field of disaster robotics is post-disaster scouting, where first-response ground robots can immediately enter the disaster area by traversing through tight spaces too small for humans. These robots are primarily designed to overcome unstable, rugged terrain. As a result, designs for these robots vary widely from tread-based movement to serpentine crawling [1]. Pleurobot, a state-of-the-art salamander robot designed by the BioRob Lab at École Polytechnique Fédérale de Lausanne (EPFL), has exhibited potential to be an effective disaster response robot due to its relatively compact and low frame, untethered battery supply, and possibility of adding I/O devices such as onboard cameras and sensors [2]. The team aims to take the first step to upgrading the Pleurobot into a controllable scouting robot by developing a more advanced control system able to traverse over small obstacles and avoid larger ones.

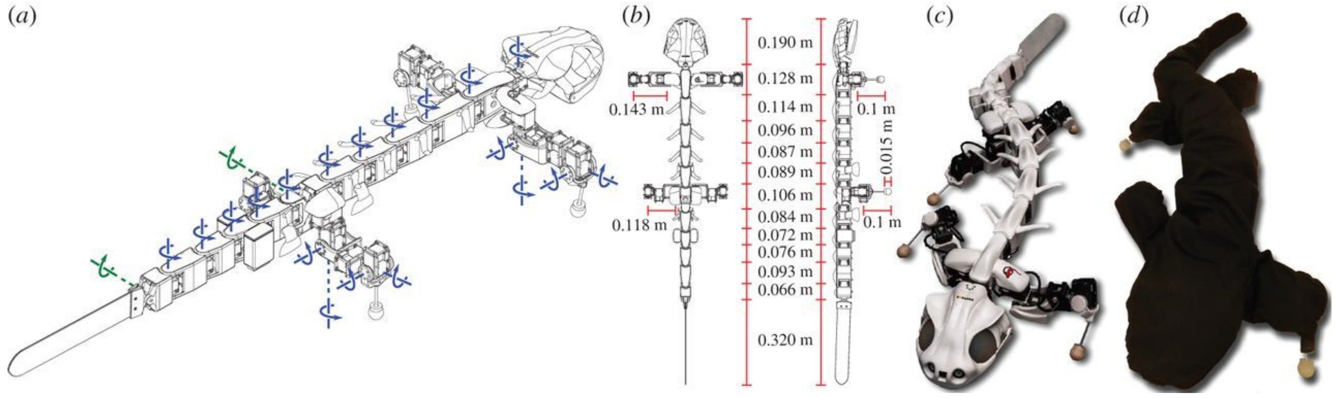


Figure 1. Degrees of freedom locations (*a)* and measurements (*b*) of the Pleurobot, with completed robot design (*c*) and swimming suit (*d*) [2].

1.3 Background and Prior Work

Our proposed salamander-based robot is similar to a large class of bioinspired snake-like robots due to its flexible spine. Snake-like robotics is a rapidly expanding research field which had its origins in the work of Hirose in the 1980s [3]. Recent snake robots include the Omnitread OT-4, a 7-segmented snake utilizing pneumatic actuators and moving tracks on the exterior [4], and a more traditional servo-based 16 degrees-of-freedom (DOF) snake by Choset et al. [5]. The IVALab at Georgia Tech has built Snakey, a 12-DOF servo-based 3D-printed snake that utilizes scale-induced frictional anisotropy to induce locomotion [6].

Free-serpentine rescue robots have also previously been developed, including the International Rescue System Institute (IRS) Soryu robot [7]. The IRS Soryu consists of three pods, each with caterpillar treads, linked by spherical joints. It also hosts a thermographic camera. Rescue robots with legs, such as the RHex [8], have demonstrated good performance over rough terrain. The RHex is a six-legged robot which uses compliant “C”-shaped-legs to achieve extremely high locomotion speeds, exceeding five body lengths per second on even terrain.

Finally, previous work in the area of biomimetic salamander-inspired robots has been done by the EPFL's Biorobotics Lab. The most advanced biomimetic robot is the Pleurobot. Pleurobot is the third salamander-inspired robot designed by the Biorobotics Lab following their previous robots, *Salamandra Robotica I* and *II*. Unlike the simplified skeleton of the previous two iterations, this biologically inspired robot was designed to more accurately replicate the kinematics structure and scaled dimensions of *Pleurodeles waltl* (*P. waltl*) with an Intel Atom 1.6 GHz computer, a more articulated spine using Dynamixel MX-64R servomotors, and additional motors placed in each limb give two more degrees of freedom. The Pleurobot's walk cycle (gait) was derived from transforming and scaling existing *P. waltl* gait data gathered from tracked cineradiography analysis and applying it to the Pleurobot's robotic joints, giving the robot a terrestrial and aquatic gait emulating that of actual salamanders [2].

2. Project Description and Goals

The goal of the Salamander Robot Team is to build a rugged salamander-like robot that is capable of traversing uneven terrain for use in disaster reconnaissance missions. The robot will consist of a 3D-printed skeleton containing at least 10 servo motors connected in series. The motors will be controlled by an on-board computer in the head running ROS (Robotic Operating System), with power supplied via a tether. A simple user interface will be constructed to allow a human operator to direct the motion of the robot, without worrying about the low-level control of each robotic joint. The user interface will consist of a joystick to command direction and speed inputs. The key features of the robot are summarized as follows:

- Bio-inspiration of salamander gait

- Robust gait control system able to traverse rough terrain
- User interface functionality for easy operator control

3. Technical Specifications

3.1 Disaster-Response Deployment Specifications

This salamander robot system is to be deployed in a disaster-response scenario. There are several specifications which are relevant to disaster-response teams who will actually be using this platform, as shown in Table 1. For example, the weight and volume need to be small enough to be man-portable for deployment, which is a useful feature in areas which may have damaged infrastructure [1]. In Table 2, the relevant performance specifications for a disaster-response robot are displayed.

Table 1. Specifications Applicable to Disaster-Response Team

Item	Specification
Weight	< 25 kg
Volume	< 2m x 0.5m x 0.5m

Table 2. Disaster-Response Related Performance Specifications

Item	Specification
Traversable terrain height deviation	> 5 cm
Traversable grade	> 3 %
Turn radius	< 2 m
Terrain traversal speed	> 10m / minute
Tether length	> 3 m

3.2 Electrical Specifications

Table 3 shows specifications for the electrical power needed for robot locomotion. For typical servomotor load while walking, 100W is estimated as necessary.

Table 3. Robot Power Specifications

Item	Average Power (W)	Maximum Power (W)
Single Robotis Dynamixel MX-28AT Servomotor	6	14
Single Robotis Dynamixel MX-64AT Servomotor	12	31
Typical total servomotor load during gait	100	200

4. Design Approach and Details

To create the proposed robot, most of the research previous done in salamander-inspired robotics will be adapted and optimized for this application. To do this, we'll take the basic concepts of the Pleurobot as well as other research on the bio-mimicry of salamanders to assemble a robot that is best configured for this application.

4.1 Design Approach

Initially, to answer the questions necessary to develop this robot, it will first be simulated mathematically to find the best size proportions and configuration of legs to both best mimic the salamander and accomplish the goals of the robot. From previous research, we already know that the leg length in combination to the distance between the sets of legs greatly affects the maneuverability and speed of the salamander. Based on this knowledge and that of other characteristic parameters of the salamander as applied to a robot, we can optimize these features to better shape the performance of the salamander robot.

Once these parameters are known, a prototype of the robot can be constructed to both act as a better tool to simulate the controls of the robot and serve as a realistic test bench for experimenting with different types of feet. Multiple feet can be tested against multiple terrains to evaluate the optimal shape, material, and orientation of the foot to then be used on the final product.

4.1.1 System Overview

A broad overview of the major components of the salamander robot system is displayed in Figure 2. The three main components aboard the robot are the processing and control computer (PCC), motor interfacing board, and servomotors. An overhead camera and associated computer provide localization data to the robot, while the PCC computer runs the operator interface and gait control algorithm. The tether (shown in gold) contains an asynchronous serial data line, as well as a 12V power line. Note all control processing is done off-board the robot, to reduce complexity and weight on-board.

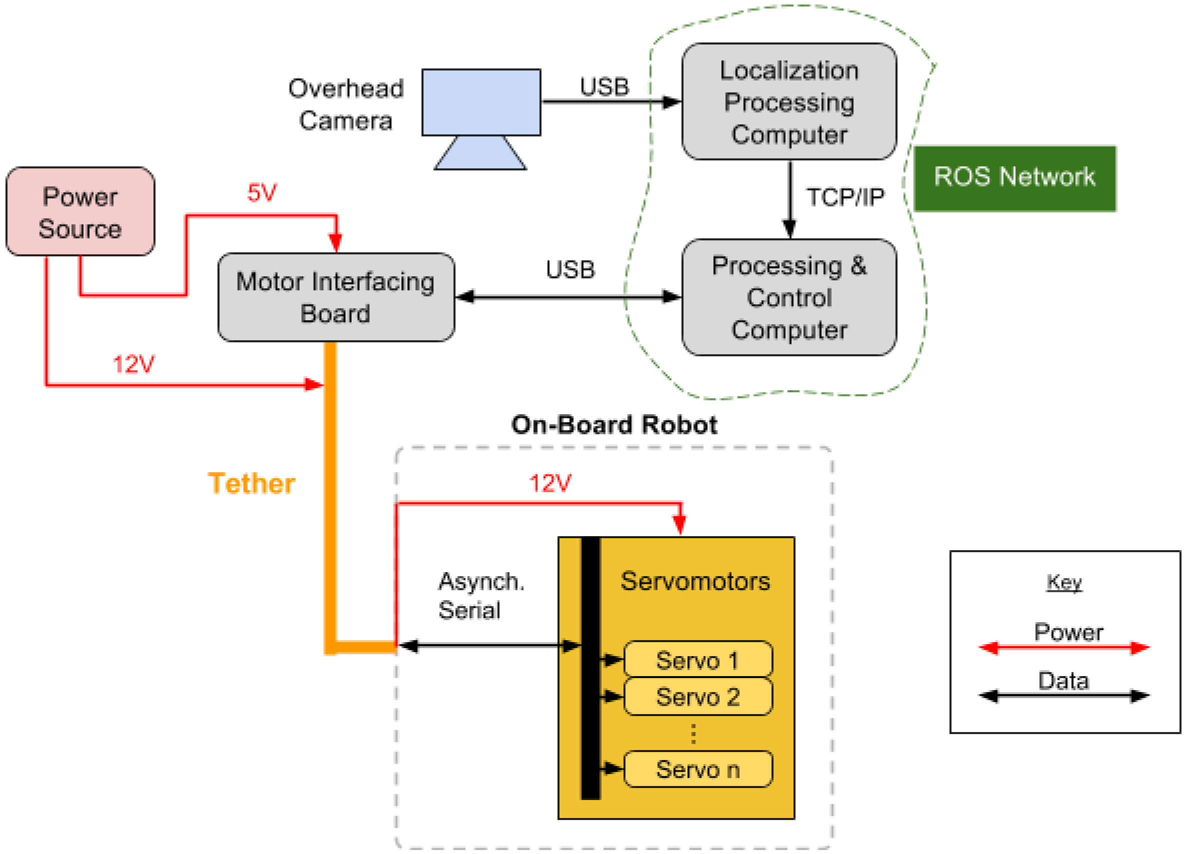


Figure 2. High-level overview of salamander robot system showing power and data connections.

4.1.2 Mechanical Design & Fabrication

4.1.2.1 Mechanical Fabrication

A mechanical engineering team will take on the mechanical fabrication of the robot, which will consist of 3D printing the robot skeleton and integrating it with servomotors and wiring. The robot design was inspired by the Pleurobot [2] from EPFL as described in Section 1.3. Using this design as a starting point, the mechanical engineering (ME) members of the team will re-design the robot to optimize it for the proposed disaster-response application. The servo motors which will be utilized for joint actuation are the Robotis Dynamixel MX-28AT and Robotis Dynamixel MX-64AT. The MX-28AT is shown in Figure 3.

Figure 3. Robotis Dynamixel MX-28AT Servomotor [9]

The general design will be based on the EPFL Pleurobot by utilizing similar 3D-printed skeletal joints. The main tool in this stage of fabrication will be a computer-aided design (CAD) suite.

Next, mechanical analysis of the robot skeleton complete with the servo motors attached will be undertaken in the CAD package. The ME team members will run tests for maximum torque required by motors, as well as weight distribution consistency are necessary to ensure the robot will function properly when constructed.

Features that enhance the robot’s ability to navigate disaster-like rubble-filled terrain will be evaluated by ME team members. Modifying the salamander’s legs to be spring-loaded, as shown in Figure 4, may prove to be one such example. Spring-loaded legs may allow the salamander to move more smoothly over uneven terrain, but they come at the cost of increased mechanical complexity and failure risk.

Figure 4. An example of a spring-loaded leg from [10].

During subsequent design iterations, tweaks and improvements will be made to the initial design as the robot's walking gait is tested. For example, if a joint's range of motion is restricted such that it impedes walking motion, some skeletal joints will need to be redesigned. If spring-loaded legs are pursued, they will also be incrementally improved in further phases.

Different foot designs will also be explored, with a rating system to judge their effectiveness on different terrain vs how important it is to be effective on such terrain. This will accomplished with a comparison of speed, complexity (risk), and terrain importance. The feet will be able to easily detach and reattach so many foot types can be tested.

4.1.2.2 Electrical Fabrication

The electrical wiring systems of the robot need to be physically fabricated, and attached to the robot skeleton. For the servomotors, power, ground, and a single data line to each motor is necessary. The motor interfacing board depicted in Figure 2 will be connected to the tether data line. The motor interfacing board is the OpenCM 9.04 board manufactured by Robotis.

A tether will also need to be fabricated, which merely consists of a power cable and an ethernet cable attached together. The overhead camera and localization processing computer will not need any fabrication because they already exist in Dr. Vela's lab.

4.1.3 Electronics Interfacing

An interfacing team will be in charge of the integration of the various computers and sensors present in the salamander robotic system. The parts to be integrated are: control computer, localization processing computer, and servomotors. The main tool for allowing all of these different pieces of hardware to communicate with one another (or integrate) is ROS (Robotic Operating System). ROS is a suite of programs that can run on many distributed computers in a TCP/IP network, which send and receive messages via a publisher-subscriber model. Each program is called a *node*. Each node publishes or subscribes to certain message *topics*. The three computers in this ROS network will communicate over Ethernet in the robot's tether, which will provide power and data connections.

4.1.3.1 Localization

The overhead camera will be connected to a Localization Processing Computer (LPC), which will publish a ROS topic of where it thinks the robot is located. It will do image processing on the overhead camera's image in order to determine the robot location. Localization interfacing will be tested by moving a test tracking object around the overhead camera's field of view, and observing how the published ROS topic changes.

4.1.3.2 On-Board Actuators

The servomotor positions will be commanded via an asynchronous serial connection running at up to 1Mbps. The SBC will have a commander node which will publish motor position commands, and a receiver node which will actually send serial data to each motor via the serial bus. The motor electronics interfacing will be tested by publishing servo motor commands to the relevant topics, and observing if the motors respond.

4.1.3.3 Power

The nominal 12V bus will be present on the robot via the tether, as shown in Figure 2. To ensure that the voltage drop over the power line will leave the servo voltage above the minimum of 10V, we calculate the resistance of the tether power line: for a tether copper power line with 1mm diameter and 5m length, the resistance is

$$R = \rho L/A = 0.1069\Omega$$

Thus, for a 15A nominal load, using $V = IR$, the voltage drop is 1.60V. So, the voltage on the servo side will be nominally 12-1.6=10.4V, which is above the 10V minimum. To ensure reliability under high loads, the tether bus voltage should be higher, preferably the highest available (14.8V).

4.1.4 Gait Control

A control subteam will be in charge of how the salamander robot will walk and move. The Pleurobot controller from [2] simply replays joint data from actual cineradiography conducted on walking and swimming salamanders. The reply data is sent from the localization processing computer with inputs from the operator via the operator control station. The replay speed is scaled to be slower, because the robot salamander is larger than a real one [2].

The first iteration of our controller will be a simple open-loop “playback” controller like the Pleurobot. The main task in this part of the controller design will be to map the Pleurobot’s video of salamander motion to our specific robot, which has different dimensions and number of joints than Pleurobot. This can be done manually or by a computer fitting tool. Next, the limb motions will be mapped to joint angles as a function of time. Finally, those joint angles will be replayed at a certain speed to create walking movement on the robot.

To test the initial iteration of the gait controller, we will determine if the robot can walk on flat surfaces and how fast the robot can walk. The gait joint angles will need to be tweaked in order to produce more efficient walking motion, as necessary. We will determine what level of roughness or unevenness is the limit before this simple "playback" controller fails and the robot cannot move. We will also experiment with running the left-side "playback" faster than the right-side, to see if the robot exhibits turning motion.

In the second iteration of the controller, we will utilize the input from four force sensors, one in each leg. Figure 5 shows how this more advanced controller will function. First, the gait controller will command a certain movement from the servomotors. Next, the motor torques will be measured to determine determine how the robot's weight is distributed. The overhead camera will also determine where the robot is and what orientation it has. Finally, the gait controller will receive the result of its movement and make another decision about how to move.

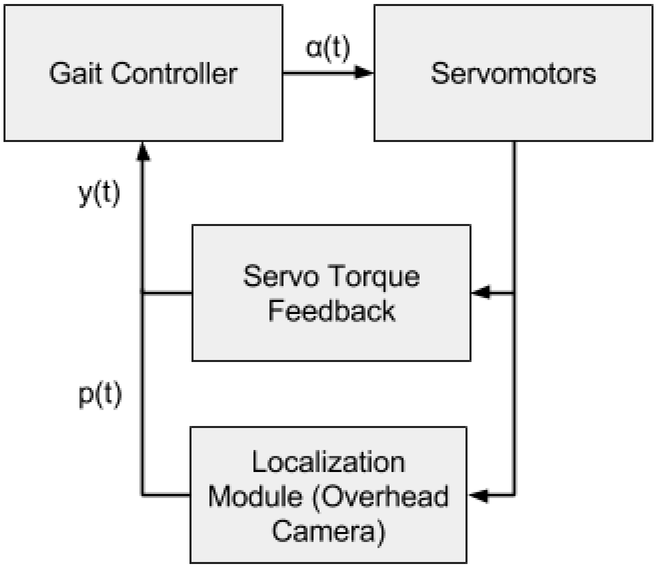


Figure 5. Illustration of gait-control feedback algorithm.

The feedback gait controller will be based on the open-loop “playback” controller, but will modify its behavior based on the weight distribution information it gets from the force sensors and based on the position and orientation information it receives from the overhead camera. For example, if the gait controller sees an obstacle in front of the robot, the controller will make the robot turn instead of going straight and colliding with the obstacle.

The second iteration of the gait controller will be tested by directing the robot to walk over more rough terrain, and observing the robot’s response to commands issued by a joystick direction/speed control input.

4.2 Codes and Standards

4.2.1 Disaster Robotics

In 2005, the U.S. Department of Homeland Security and the National Institute of Standards and Technology (NIST) developed a suite of standard test methods to “quantify key capabilities of robots for emergency response and other hazardous applications” [11]. The result was DHS-NIST-ASTM: “International Standard Test Methods for Response Robots measures robot maneuvering, mobility, manipulation, sensing, endurance, radio communication, durability, reliability, logistics, and safety for remotely operated ground vehicles, aquatic vehicles, and small unmanned aerial systems in FAA Group I under 2 kg (4.4 lbs)” [11].

One relevant testing standard for the salamander robot in question is the “Disaster City” standard test bed, as shown in Figure 6. The testbed begins with flat, sloped terrain, and slowly works up to real rubble of various dimensions. The challenge for the robot is to make it from beginning to end of the test bed. We will operate the robot in a variety of conditions similar to a “Disaster City” by making the robot walk on variously sized gravel, ramps of up to 30 degrees, and finally, if time permits, stairs.

Figure 6. NIST “Disaster City” Standard Test Bed from [11]

4.2.2 Interfacing

The main interfacing standards utilized in this salamander robotic system are summarized in Table 4.

Table 4. Communication Standards for the Robot Salamander System

Standard	Features	Components Utilizing
TCP/IP over Ethernet (Transmission Control Protocol/Internet Protocol)	High data rates of over 10 Mpbs Bidirectional communication Twisted pair	Localization Processing Computer, SBC, Command Computer, ROS communication
Asynchronous TTL Serial (Transistor-Transistor Logic)	Up to 1 Mbps transmission speed Bidirectional communication 3.3 or 5V No clock signal	Servomotors
USB (Universal Serial Bus) 2.0	480 Mbps Master/slave relationship No clock signal	Communication to interfacing board

4.3 Constraints, Alternatives, and Tradeoffs

4.3.1 Constraint: Weight/Number of DOF

One of the most important constraints for the robot salamander system is the number of servomotors, or DOF. The larger the number of DOF, the more flexible and robust it can be to rough terrain. However, the larger the DOF, the heavier and more unwieldy the robot becomes. In addition, the longer the motor chain, the higher the torque requirements. So, the ideal design is not to slow and heavy, but has enough DOF to be flexible enough to traverse difficult terrain.

4.3.2 Tradeoff: Tethered vs. Untethered

Eliminating a tether and utilizing an on-board battery would free the robot from the distance-limitations and excess drag force of a power tether. A data tether could be eliminated by using a wireless network such as WiFi. On the other hand, a power tether would be beneficial because it provides unlimited operating life and reduced on-board weight. A battery would significantly increase robot weight and volume. The weight contributions between an on-board battery vs. pulling a long tether are nearly equal, and both limit operating range, so cost and complexity of each solution was the main determining factor. The tether is much cheaper and less-complex solution than buying a large battery pack and associated battery monitoring system.

5. Schedule, Tasks, and Milestones

A Gantt chart showing the project timeline and tasks to be completed is presented in Appendix A. The Gantt chart shows the team structure, which is also displayed in Figure 7. The team is divided into three subteams: mechanical, control, and interfacing. These teams will work in parallel throughout the course of the semester as shown in the Gantt chart.

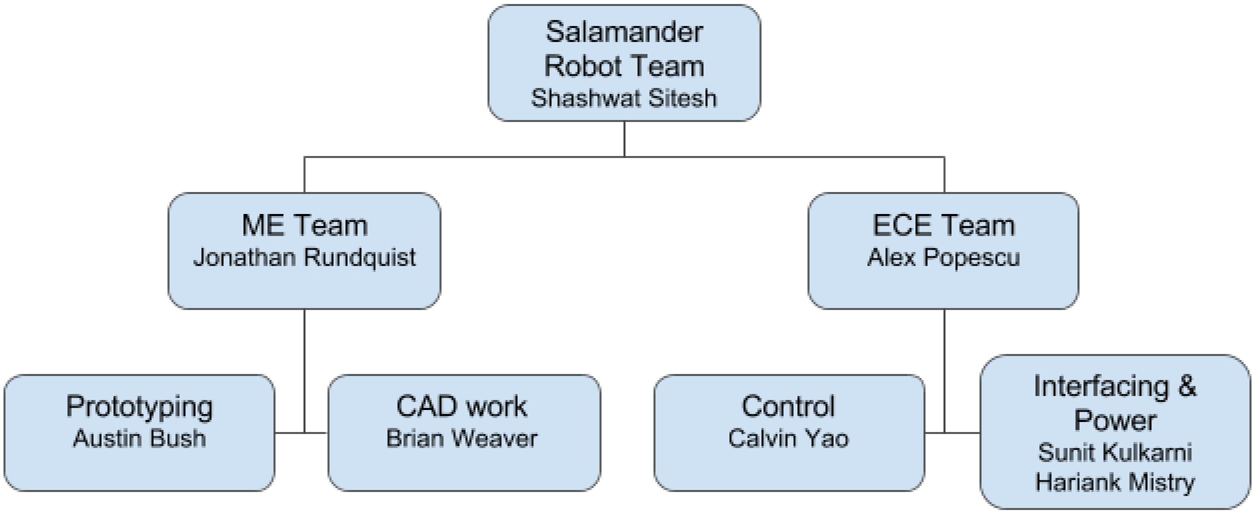


Figure 7. Team organizational chart

6. Project Demonstration

The project demonstration will take place in a Georgia Tech lab setting (Dr. Vela's lab) and will test the planning and mapping capabilities of the salamander robot by demonstrating its ability to traverse rough terrain. The robot will be tested over several platforms of rough terrain and obstacles to examine the versatility of the robot. The demonstration will highlight the following:

1. Walking and turning gaits over terrain with varying levels of surface roughness.
2. Walking and turning gaits over terrain with holes and slats that would get a wheeled robot caught.

6.1 Demonstration Steps

1. Give simple joystick controller to audience member and direct to do the following:
2. Walk over straight ground.
   a. Attempt turning and straight gait movements.

3. Walk over rough ground (feature size < 0.1m).
4. Walk over terrain with numerous holes or jagged edges that would be difficult for a wheeled or tracked robot to traverse.

7. Marketing and Cost Analysis

7.1 Marketing Analysis

At this time, disaster robots are not routinely sold in quantity, as this field is still under research and any completed robots are used by governments, companies, and universities. According to [12], government agencies and humanitarian organizations dealing in emergency response can expect to pay in increments of $50,000 for “small ground robots.” However, larger caterpillar robots are valued in the range of $100,000. The market for disaster robots is also small: only 37 deployments have been reported for disaster robots since 2001 [1]. Clearly, disaster robots comprise a small and expensive market. The total development costs of our salamander robot (detailed in the next two sections) fit in this high price range, as expected.

7.2 Cost & Funding Analysis

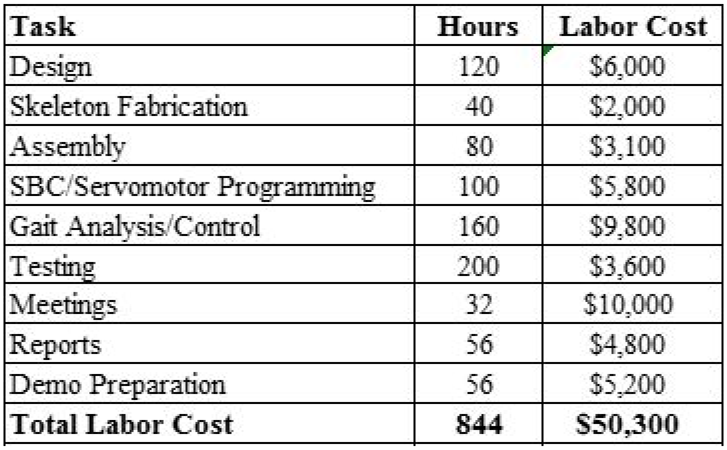
The total parts cost for a prototype of the salamander robot is calculated as $4,789.30, as shown in Table 5. The most costly components are the Dynamixel servomotors, which cost $239.90 apiece for the Dynamixel MX-28AT model. All individual component components and associated costs are displayed in Table 5.

Table 5. Parts Costs

Item	Unit Price	Quantity	Total Price
Dynamixel MX-28AT Servomotor (Dr. Vela)	$239.90	12	$2,878.80
Dynamixel MX-64AT Servomotor (Dr. Vela)	$258.25	6	$1,549.5
Tether materials (senior design lab)	$10.00/m	5	$50.00
3D printing material (ECE printer)	$1.00/cm^3	300	$300.00
Total Parts Cost			$4,798.30

Labor costs were calculated assuming $50 per hour. Gait analysis/control and testing are expected to have the most labor-hours due to the difficulty of implementing and testing the walk cycles of the robot. The breakdown of the development costs are listed in Table 6.

Table 6. Development Costs



Task	Hours	Labor Cost
Design	120	$6,000
Skeleton Fabrication	40	$2,000
Assembly	80	$3,100
SBC/Servomotor Programming	100	$5,800
Gait Analysis/Control	160	$9,800
Testing	200	$3,600
Meetings	32	$10,000
Reports	56	$4,800
Demo Preparation	56	$5,200
Total Labor Cost	**844**	**$50,300**

Assuming fringe benefits are 30% of labor and overhead on materials, and overhead costs are 120% of parts, labor, and fringe benefits, the total development cost of this salamander robot is $154,394.46, according to Table 7.

Table 7. Total Development Costs

Development Component	**Cost**
Parts	$4,798.30
Labor	$50,300.00
Fringe Benefits (30% labor)	$15,090.00
Subtotal	$70,179.3
Overhead (120% of parts, labor, fringe)	$84,215.16
Total Development Cost	$154,394.46

Funding for our project will come from two main sources: Dr. P. Vela's lab, as well as the ECE department. The amount from each funding source is shown in Table 8. Funding from the ECE department is estimated at about $100 per team member.

Table 8. Funding Sources and Amounts

Funding Source	**Amount**
Dr. P. Vela/IVALab	$4,798.30
ECE Department	$800.00
Total Available Funds	$5,598.30

The available funding of $5,598.30 is enough to cover the parts costs of $4,798.30, with $800.00 for additional unforeseen costs.

7.3 Profit Analysis

As described in Section 7.1, medium-size ground-based disaster robots near the scale of our salamander robot are routinely sold for $100,000 and more. The total development costs of our robot are estimated at $154,394.46. So, if the proposed salamander robot is sold for $200,000.00, the profit will be $45,605.54. This price is in the normal competitive price range for disaster robots of this scale, and still yields a reasonable 22.8% net profit margin.

8. Current Status

The mechanical engineering team is currently researching foot design strategies and designing the repeated module joint that will be utilized throughout the robot. The control team is in the modeling and simulation phase, and is determining the optimal physical sizes and gait parameters for the robot. The interfacing team is working to estimate power requirements and research the servo actuators. In addition, all teams are reading peer-reviewed articles relating to their tasks, to assist with the research-heavy nature of this project.

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Appendix A: Gantt Chart

The Gantt chart for this project is on the following page.