Amphibious Spherical Explorer

Design Review

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ECE 445 Senior Design, Spring 2016
Project No. 30
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February 29, 2016
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1 INTRODUCTION

1.1 Title and Objectives

This project intends to build an amphibious spherical explorer (ASE), which is a spherical robot that can perform data collection tasks on land or in water. Our concentration in ECE is control system. Therefore, we want our senior design to be an application of control. Inspired by spherical robots in movies such as Star Wars and Jurassic World, we decided to create one of our own. After we conduct a series of researches on spherical robots that are currently in the market, we come to realize those robots are run on a fairly unstable mechanism which causes wobbly movements. Therefore, we would like to challenge our knowledge on control by using a different implementation which may eliminate the instability issue that we observe from those other spherical robots.

1.1.1 Goals

- Eliminating wobbly movements.
- Optimizing the size of PCB board.
- Improving the robustness against collision.

1.1.2 Functions

- Traveling in extreme conditions such as water, desert, swamp, etc.
- Collecting data using interchangeable task module
- Sending control signal from PC to the explorer.

1.1.3 Features

- Pendulum drive mechanism.
- Superior mobility and versatility.
- Expandability to various interchangeable task modules

1.1.4 Benefits

- Spherical shape enables the robot to pass low-accessible areas.
- Improvement balance control makes the robot perform stability-demanded tasks like videoing.
2 DESIGN

2.1 Block Diagrams

![Block Diagram of the System](image)

Figure 1. Block diagram of the system.

2.2 Block Descriptions

2.2.1 Control Site

The control site is the personal computer that runs a program (tentatively MATLAB) for communication. This program mainly perform two tasks: sending commands to the robot to control the actions, as well as receiving and decoding the information sent back from the robot. Communications in both directions are completed via IEEE 802.11 (WiFi) and User Datagram Protocol (UDP). The WiFi access point is created by the control site.

2.2.2 WiFi Module

WiFi Module is the communication module of the robot. The WiFi module works in passive mode, which only connects to the access point created by the control site, and works as client, which periodically sends and pulls data from the server, the control site.

2.2.3 Servo

The servo control the relative position between the spherical shell and the internal weight of the robot. By shifting the center of mass with a deviation from the vertical, the servo can adjust the balance and control the turn when moving forward or backward.
2.2.4 Motor Driver

The motor driver is a switch or amplifier. There is a MOSFET H-bridge circuit inside the motor driver. Its on/off state is controlled by the square waves generated by the microcontroller. The duty cycle of the square wave will determine the effective voltage applied on the motor and therefore control the power of the motor. This is known as Pulse Width Modulation (PWM).

2.2.5 DC Motor

The DC motor drives the robot forward and backward. Unlike ordinary wheeled vehicle motors, it does not drive the robot directly. This motor, along with the mass, hangs on a fixed axle inside the sphere. When moving forward, the motor gives the mass that hangs on the motor a disturbance to the front, away from the vertical. At the same time, the gravitational torque will drag the whole robot rolling forward. Repeating this process will keep the robot moving forward.

2.2.6 Inertial Measurement Unit (IMU)

The IMU consists of a three-channel gyroscope and a three-channel accelerometer. Data from the both sensors can be transformed into attitude angles with the help of a patented algorithm. However, since we do not pay for such algorithm, a simplified version will be developed and used as substitute.

2.2.7 Magnetic Encoder

The magnetic encoder is a sensor measuring the angular displacement of the rotor of DC motor. The sensor consists of a Hall effect sensor and a magnet. When the magnet rotates along with the rotor, the Hall effect sensor can measure the change of magnetic field and return the angle rotated. Angular speed of the rotation can also be obtained by differentiating the angle measured.

2.2.8 Microcontroller

The microcontroller is the core of the system, which takes charge of control and signal processing. It implements the following functions:

- Reading/transmitting data from/to sensors and the communication module via I²C, SPI and UART.
- IMU Algorithm implementation.
- Controller implementation.
- Control on actuators using PWM.

2.2.9 Task Module

As a feature of “modular design”, the task modules are modules for extended use. The modules communicate with the microcontroller via I²C (some of them UART) to perform different tests. Some tentative choices, including temperature sensors, audio recorder or even digital camera, are commercially available. As long as the corresponding library are built as interface to the firmware, the users can customize their robot according to their purposes.
2.3 Technical Overview

Due to the inevitable yet unforeseeable adjustments that will be made, this project will require a fair amount of time investment. Unlike a typical embedded systems project, it is much more complicated to modify a control systems project. Changes will more than likely involve changing multiple mechanical parts as well as adding and replacing the existing electrical components. In addition, we also need to make individual parts compact enough to integrate perfectly. This implies that a lot of effort will be spent in minimizing the area of the PCB while being able to integrate all the electrical and mechanical components into one package.

In order for the robot to sustain in harsh collisions, we decided to use soft plastic shell as the outer surface. Interchangeable task module will be implemented to achieve the goal of data collecting. As for communication between PC and robot, our team will be transmitting signal and data through WIFI.

The robot uses the continuous track mechanism to drive the spherical explorer from the inner surface. Comparing to other spherical robots, like Sphero, in the market, this project uses gravitational torque to generate the forward movement. In addition to the gravity torque, a servo will be used to control the position of the mass in a perpendicular axis. This allows us to control roll motion which helps eliminate oscillation during turning. Another unique thing about our robot is the communication via WIFI while most of the others use Bluetooth connections.

2.4 Schematic

![System schematic.](image)

2.5 Mechanical Design

The most common mechanism to drive a rolling robot is based on an internal car-like actuator. The shell rolling forward as the car inside the shell runs forward. This design is the easiest to design but suffered from a coupling effect between the control on pitch angle and roll angle, since the output of the car-like actuator does not exert on the angles seperately. Another method is to use a flying-wheel-based mechanism [1]. This
design actuate the robot when the robot exchanges angular momentum with the flying wheels. But when the flying wheels rotate too fast, the motors that rotate the flying wheels will saturate and no longer give correct torques to control the robot.

The design of ASE uses a pendulum mechanism. The main motor raise the weight hanging below it from the equilibrium position and makes the robot moving forward or backward. Another servo motor actuates the weight latitudinally, controlling balance and making turning actions. The diameter of the robot is 140 mm and the weight with battery is around 500 g. The visualized design is shown in Figure 3 and Figure 4.

![Figure 3. Assembly diagram of ASE.](image)

![Figure 4. Parts explosion diagram of ASE.](image)

### 2.6 Derivation and Simulation

Since a rolling system like ASE is nonholonomic, a complete dynamic analysis of such system is related to Lagrange equations of the first kind [2]. On the current stage, we are not going to give the complete derivation
of dynamic model, and mainly use an experiment-based model as well as a set of controller parameters based on trial-and-error.

However, understanding the mechanics behind the turning motion is necessary for controller design. When the robot is making a turns, how much actuation angle $\alpha$ the servo should shift the mass is related to the turning radius $r$ demanded, and the velocity $v$ at which the robot is running at. The non-linearity of such relation makes generic linear controller to be less effective. To clarify this relation, here we give a short analysis based on Newton method and D’Alembert principle.

![Figure 5. Sketch for mechanical analysis on turning motion.](image)

Define the roll angle of the robot as $\phi$, the actuation angle of the servo as $\alpha$, the radius of the spherical shell as $R$, the distance between the center of mass (CoM) and the geometric center as $l$, and the turning radius as $r$. Figure 5 shows the geometry relations between these quantities.

In a smooth turn, D’Alembert principle indicates the net torque with respect to the contact point with ground (including the torque caused by inertial forces) should be

$$\sum_i M_i = mglsin(\alpha - \phi) - \frac{mv^2}{r}(R - lcos(\alpha - \phi)) = 0$$

Simplifying, we have

$$glrsin(\alpha - \phi) = v^2(R - lcos(\alpha - \phi))$$

$$v^2lcos(\alpha - \phi) + glrsin(\alpha - \phi) = v^2R$$

$$l\sqrt{v^4 + g^2r^2}sin((\alpha - \phi) + atan(v^2gr)) = v^2R$$

Note that $r = R\cot \phi \Rightarrow \phi = atan(\frac{R}{r})$, we obtain

$$\alpha = asin\left(\frac{v^2R}{l\sqrt{v^4 + g^2r^2}}\right) + atan\left(\frac{R}{r}\right) - atan\left(\frac{v^2}{gr}\right)$$
On-chip computation for actuation angle $\alpha$ is almost impossible for microcontroller, however, we can prepare the value needed and use look-up-table method on microcontroller. A simulation of controller reaction at different turning radii is shown in Figure 6.

Figure 6. Servo actuation angle vs. velocity.
## 3 REQUIREMENTS AND VERIFICATION

### 3.1 Requirements and Verification

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification</th>
<th>Verification Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum turning radius &lt; 1m</td>
<td><strong>Empirical Verification:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Take a 2 m$^2$ of an area and operate robot within</td>
<td></td>
</tr>
<tr>
<td></td>
<td>this specified area.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• If full circle can be made without robot leaving</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the area, then this requirement can be confirmed.</td>
<td></td>
</tr>
<tr>
<td>Average acceleration &gt; 0.2 m/s$^2$</td>
<td><strong>Empirical Verification:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Drive the robot forward (from rest) from point a to b.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Sample speed and time and approximate acceleration by taking several derivatives.</td>
<td></td>
</tr>
<tr>
<td>Maximum Speed &gt; 1 m/s</td>
<td><strong>Empirical Verification:</strong></td>
<td>The angular speed of the DC Motor was tested over the period of one minute. The motor was measured to spin 0.8 rev/s. Using this to turn the gear on the axle with a ratio of 1/3 allowed the gear to turn 2.4 rev/s. The circumference of the shell is 0.44m. $0.44m \times 2.4/s = 1.056m/s &gt; 1m/s$. By testing the speed of the DC Motor and choosing appropriate gear ratio, this requirement is fulfilled.</td>
</tr>
</tbody>
</table>
### 3.2 Tolerance Analysis

Due to the nature of the robot being remotely controlled, it is very difficult to change the batteries of the robot. Therefore, power is critical to successful operation. To ensure that the robot can travel to the destination and back, power consumption must be accurately calculated and thoroughly tested.

An estimation of the total power is calculated by extracting information from the datasheets of the basic components. For bare minimum functionality at normal operation mode, the following items are tested: DC motor, High Speed Servo, Freescale MK20DX256 MCU, and a AS5048A Magnetic Encoder. The power consumption of each component is extracted from datasheets as follows:

<table>
<thead>
<tr>
<th>Components</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxon A-max 22 diameter DC motor</td>
<td>0.5 W (loaded)</td>
</tr>
<tr>
<td>HD-3688HB High Speed Servo</td>
<td>1.3 W</td>
</tr>
<tr>
<td>Freescale MK20DX256 MCU</td>
<td>108 mW</td>
</tr>
<tr>
<td>AS5048B Magnetic Encoder</td>
<td>150 mW</td>
</tr>
<tr>
<td><strong>Estimated Total Power</strong></td>
<td><strong>2.058 W</strong></td>
</tr>
</tbody>
</table>

#### Table 2. Power Consumption of Components
4 COST AND SCHEDULE

4.1 Cost Analysis

4.1.1 Labor

\[
\text{Labor Cost} = \text{Hourly Rate} \times \text{Total Hours} \times \text{Number of People} \\
= 25.00 \times 400 \times 3 \times 2.5 \\
= 75000
\]

4.1.2 Parts

Table 3. Parts Costs

<table>
<thead>
<tr>
<th>Part</th>
<th>Quantity</th>
<th>Cost($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WiFi Module</td>
<td>1 pc</td>
<td>34.95</td>
</tr>
<tr>
<td>Servo</td>
<td>1 pc</td>
<td>19.95</td>
</tr>
<tr>
<td>Motor Driver</td>
<td>1 pc</td>
<td>4.49</td>
</tr>
<tr>
<td>DC motor</td>
<td>1 pc</td>
<td>20.00</td>
</tr>
<tr>
<td>IMU</td>
<td>1 pc</td>
<td>6.84</td>
</tr>
<tr>
<td>Magnetic Encoder</td>
<td>1 pc</td>
<td>15.00</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>1 pc</td>
<td>19.80</td>
</tr>
<tr>
<td>Camera (task module)</td>
<td>1 pc</td>
<td>7.27</td>
</tr>
<tr>
<td>Plastic Ball</td>
<td>1 pc</td>
<td>2.49</td>
</tr>
<tr>
<td>3D Print Filament</td>
<td>1 roll</td>
<td>18.00</td>
</tr>
<tr>
<td>Gears</td>
<td>2 bags</td>
<td>3.92</td>
</tr>
<tr>
<td>Li-Po Battery</td>
<td>2 pcs</td>
<td>49.88</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>202.59</td>
</tr>
</tbody>
</table>

4.1.3 Grand Total

\[
\text{Grand Total} = \text{Labor Cost} + \text{Part Cost} = 75202.59
\]
### 4.2 Schedule

Table 4. Project Schedule and Weekly Deadlines

<table>
<thead>
<tr>
<th>Week</th>
<th>Tasks</th>
<th>Students</th>
<th>Major Tasks Due</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-Feb</td>
<td>Work on proposal together.</td>
<td>All</td>
<td>Project Proposal due (Wed).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mock Design Review Sign up (Thu).</td>
</tr>
<tr>
<td>15-Feb</td>
<td>Write firmware for controlling motor using motor driver.</td>
<td>Kaiwen Chen</td>
<td>Mock Design Reviews (Tue-Thu).</td>
</tr>
<tr>
<td></td>
<td>Attached axle to ball and 3d printed motor/servo chamber.</td>
<td>Zhong Tan</td>
<td>Eagle Assignment due (Fri).</td>
</tr>
<tr>
<td></td>
<td>Rough estimation of component placement on PCB.</td>
<td>Junhao Su</td>
<td></td>
</tr>
<tr>
<td>22-Feb</td>
<td>Write firmware for servo.</td>
<td>Kaiwen Chen</td>
<td>Design Review Sign up (Mon).</td>
</tr>
<tr>
<td></td>
<td>Attach gears to axle and align gears properly.</td>
<td>Zhong Tan</td>
<td>Eagle Assignment due (Fri).</td>
</tr>
<tr>
<td></td>
<td>Sketch PCB layout according to rough draft.</td>
<td>Junhao Su</td>
<td>Soldering Assignment Due (Fri)</td>
</tr>
<tr>
<td>29-Feb</td>
<td>Write I$^2$C code for gyroscope.</td>
<td>Kaiwen Chen</td>
<td>Design Reviews (Mon-Wed).</td>
</tr>
<tr>
<td></td>
<td>Attach mass to servo.</td>
<td>Zhong Tan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Continue with PCB layout.</td>
<td>Junhao Su</td>
<td></td>
</tr>
<tr>
<td>7-Mar</td>
<td>Ability read signal from magnetic encoder.</td>
<td>Kaiwen Chen</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ensure the stability of the mechanical infrastructure.</td>
<td>Zhong Tan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Submit first PCB to manufacturer + prototype board .</td>
<td>Junhao Su</td>
<td></td>
</tr>
<tr>
<td>14-Mar</td>
<td>Ability to control speed of motors and servo orientation.</td>
<td>Kaiwen Chen</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Placement of the magnetic encoder into mechanical design.</td>
<td>Zhong Tan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Test protoboard.</td>
<td>Junhao Su</td>
<td></td>
</tr>
<tr>
<td>21-Mar</td>
<td>Attempt to integrate separate components into one package and test as a team.</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td>Week</td>
<td>Tasks</td>
<td>Students</td>
<td>Major Tasks Due</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------------------</td>
<td>-----------------</td>
<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>28-Mar</td>
<td>Ability to connect WiFi module to WiFi network.</td>
<td>Kaiwen Chen</td>
<td>R&amp;V Table (2nd Attempt) due (Mon). Individual Progress Report due (Mon).</td>
</tr>
<tr>
<td></td>
<td>Revisit any mechanical failures.</td>
<td>Zhong Tan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Receive PCB board from manufacturer. Solder and test. Solder and test. Submit second edition of PCB layout to manufacturer if first try doesn't work.</td>
<td>Junhao Su</td>
<td></td>
</tr>
<tr>
<td>14-Mar</td>
<td>Ability to send data over WiFi.</td>
<td>Kaiwen Chen</td>
<td>R&amp;V Table (Final Attempt) due (Fri).</td>
</tr>
<tr>
<td></td>
<td>Prepare final form of robot.</td>
<td>Zhong Tan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prepare an alternative for PCB while waiting for second edition.</td>
<td>Junhao Su</td>
<td></td>
</tr>
<tr>
<td>11-Apr</td>
<td>Ability to receive signal over WiFi.</td>
<td>Kaiwen Chen</td>
<td>Mock Demos during TA meeting</td>
</tr>
<tr>
<td></td>
<td>Create spare parts for robot in case things go wrong for demo.</td>
<td>Zhong Tan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Finalize components into PCB.</td>
<td>Junhao Su</td>
<td></td>
</tr>
<tr>
<td>18-Apr</td>
<td>Finalize robot for demonstration.</td>
<td>All</td>
<td>Demonstration Sign up (Mon). Mock Presentation Sign up (Mon). Presentation Sign up (Mon).</td>
</tr>
<tr>
<td>25-Apr</td>
<td></td>
<td>All</td>
<td>Demonstrations (Mon-Wed). Mock Presentation (Thu,Fri).</td>
</tr>
<tr>
<td>2-May</td>
<td></td>
<td>All</td>
<td>Presentations (Mon-Wed). Final Papers due (Wed). Lab Notebook Due (Thu).</td>
</tr>
</tbody>
</table>
5 SAFETY AND ETHICAL ISSUES

5.1 Safety Statement

This project consists of both mechanical and electrical components leading to both mechanical and electrical safety concerns.

- **Mechanical safety**
  This project will require the use of a small amount of power tools such as drills and saws. Proper safety precautions will be taken accordingly. We will be working with some power tools outside of the Senior Design lab. Goggles will be worn at all times during the drilling and sawing process. Gloves will also be worn by each member during the power tool process.

- **Electrical safety**
  In the prototype and PCB development stage, a substantial amount of soldering will be involved. Appropriate safety precautions will be taken. Fume extractor will be used throughout the soldering process to minimize harmful fumes in the room.

  We will be using Lithium Polymer batteries (LiPo) batteries for their superiority in energy capacity, fast charging speed, and high output current. These batteries must be handled with care. We have read general safety guidelines [3] for the LiPo batteries from the manufacturer and will be following each guideline carefully.

5.2 Ethical Issues

The project obeys IEEE Code of Ethics as followed [4]:

- to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;
- to avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist;
- to be honest and realistic in stating claims or estimates based on available data;
- to reject bribery in all its forms;
- to improve the understanding of technology; its appropriate application, and potential consequences;
- to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations;
- to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others;
- to treat fairly all persons and to not engage in acts of discrimination based on race, religion, gender, disability, age, national origin, sexual orientation, gender identity, or gender expression;
- to avoid injuring others, their property, reputation, or employment by false or malicious action;
• to assist colleagues and co-workers in their professional development and to support them in following this code of ethics.
6 REFERENCES


