Implementation of a Higher Order Sliding Mode Controller on a Legged Rover

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Implementation of a Higher Order Sliding Mode Controller on a Legged Rover

By

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\[ 5/14/18 \]

Honors College Dean (signature) Date
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Date
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Abstract

A closed loop, High Order Sliding Mode control algorithm is implemented and tested against previous attempts that used different control approaches. A 4-legged robot is constructed using linear actuators to demonstrate the HOSM controller. Static platforms are used to test the system response for constant inclinations. A dynamic testing platform is constructed to test the system response to dynamically changing inclinations. The design of hardware systems, software systems, and testing procedures are discussed along with testing results.
Introduction

With the insurgence of deep space exploration interest, unmanned vehicles will no doubt be deployed to planets to explore and collect samples before any manned missions are conducted. They will be first sent to scout unknown territories and then be used in unmanned missions to explore areas that are hazardous and unreachable to humans. The primary vehicles for ground based exploration are rovers. Figure 1 below shows an example of a rover used for space exploration.

![Curiosity Rover](image)

*Figure 1: Curiosity Rover [1]*

When it comes to rovers, there are multiple configurations. There could be legged rovers, wheeled rovers, leg-wheeled rovers, and many others. When considering legged rovers, they offer the benefits of keeping the same level of stability, which means all the legs will always stay on the ground. When considering wheeled robots, they offer benefits of increased speed and simplicity. While self-leveling suspensions do exist for wheeled robots, like smart suspensions in certain sports cars, the drawback is that there are situations where not all wheels are on the ground. This occurrence can be avoided using robots with adjustable legs [2]. To combine the benefits of both wheels and adjustable legs, this project uses a robot with 4 length-adjustable legs to which wheels can also be attached in future iterations.
Background

The focus of this paper is not kinematics and control of the legged robot as these were already developed[2], however, a general background of control systems concepts and the specific kinematics and control systems of the constructed robot will be helpful in fully understanding the implications of this research. The kinematics and the controls of the robot were designed and simulated by Swaroop Kotike and Dr. Fahimi [2]. Figure 2 below shows the configuration of the robot.

![Figure 2: Rover Kinematics [2]](image)

The angles $\alpha$ and $\beta$ represent the roll and pitch angles of the robot respectively, and $l_1$, $l_2$, $l_3$, and $l_4$ represent the lengths of each leg.

To control the robot, a high order sliding mode controller (HOSM) was developed. A HOSM is used in this case because it assumes a nonlinear relationship between input (desired roll and pitch) and output (leg velocity commands) of the control system. The reason for this is apparent in the observed results when assessing HOSM performance vs. linear controllers for this application.

The specific system that is tested is decomposed into three blocks in a closed-loop system shown in Figure 3 below.
The plant refers to the system being controlled, which is the legged rover that is pictured above the testing platform. The sensor is the VICON motion capture camera system, which keeps track of the robot leg lengths and body angles. The controller is the HOSM, which takes in the sensor data and outputs leg velocity commands that are applied to the plant. The physical system works by using a computer in the UAH’s ATOM lab that is connected to a VICON system to read required input data. This data is then input into the HOSM controller, which is implemented in MATLAB on the same computer. The output commands from the MATLAB script are sent to a separate laptop through TCP/IP communication. This laptop then relays these commands through another MATLAB script to the Arduino® microcontroller onboard the robot. The Arduino® on the robot then relays those commands to the onboard motor controllers to adjust the leg lengths and level the robot.
**Systems Design**

**Plant**

Robot

For a robot with the same kinematics as discussed previously, legged rovers from previous senior design projects were to be used; however, these were not operational. These robots are pictured in figure 4 below. These legs work using gears and threaded rods.

![Previous Robot Model](image)

*Figure 4: Previous Robot Model*

Because of the complex gear system of the original senior design robot, diagnosing and fixing problems to make it functional within the allotted time frame was unfeasible because of how the system was assembled. Instead of copying the design from the old senior design projects, a simpler, and equally effective robot was designed using linear actuators and an acrylic plate. The constructed robot is shown in Figure 5 below. With the new linear actuator model, if there is a problem with one of the legs, all that must be done is the replacement of the linear actuator with a new one. In the newly constructed robot, Arduino® microcontroller and motor speed controllers are mounted onto the acrylic plate.
To measure the current roll angles, pitch angles, and velocities, a VICON motion capture system is used. This system consists of cameras that are used to triangulate the positions of reflective markers. In figure 5, there are two markers placed on each leg (one fixed and one free) to determine leg velocity and three markers placed on the robot body to determine roll and pitch angles. The software used is VICON tracker because of its ability to track markers in real time. A visualization of the 3D model is shown in figure 6 below.

Testing platform

The controller is designed to work for angles up to 45 degrees and angular rates of 1.5 degrees per second. Such speed and range of motion can be achieved by using gear motors and chain. With simplicity in mind, a simpler testing platform was developed based on the principle
of the legged rover to emulate the functionality of gear motors and chains. The table (the testing platform), can be seen with the robot on top of it in figure 7 below.

![Robot on Testing Platform](image)

Figure 7: Robot on Testing Platform

Similar to the design of the robot, two linear actuators were used to raise and lower the table. A rod with a ball joint at the end of it is placed opposite to the linear actuators. The available ball joint with the largest possible range of motion was 30 degrees, allowing the robot to be tested only to an angle of 30 degrees. However, this is sufficient to prove the robustness and accuracy of the controller.

**Code**

First the roll and pitch angles and leg lengths are calculated from the VICON markers. Next, the roll and pitch angles and leg lengths are input into the control algorithm, and the control algorithm will return leg velocity commands. These leg velocity commands (m/s) are converted to eight bit values through derived calibration equations. The calibration equations.

The calibration equations for each actuator were derived by plotting applied R/C commands with recorded leg velocities from VICON tracker. Figure 8 shows the testing setup to determine the calibration equations.
Figure 8: Leg Calibration Setup

Figure 9 below shows the results of the calibration tests for each leg. The data from the tests were plotted in excel and a linear curve fit was used to get the calibration equations.

Another important part of the code are the gains of the controller. For scope of this paper, it is important to know that gains effect the stability of a closed loop control system. The stability of a system includes the time it takes to reach steady state and the oscillations of the system. For this project, the gains were picked using trial and error to minimize oscillations with less importance placed on the amount of time to reach steady state.
Experiment Design and Procedure

Experiments were designed to showcase performance of the HOSM controller in three different scenarios: uphill constant incline, lateral constant incline, and dynamically varying incline.

The first two tests start with the robots on a constant incline and then activates the controller to see if the rover can reach a steady state with minimum steady state error. The testing setups for the constant incline tests are shown in figure 10 below (after stabilization).

![Stationary Testing Setup](image1)

The third test is not only to test if roll and pitch can stabilize on a constant incline, but if roll and pitch can stabilize dynamically at a speed of 1.5 degrees/second. The test setup is shown below.

![Dynamic Testing Setup](image2)

Figure 11 above shows the full terrain variation range of the dynamically varying test.
Results

Below in figure 12 are the results of the constant uphill slope test.

![Figure 12: Uphill Test Results [2]](image)

From the figures above the approach of both roll and pitch to steady state are relatively quick at less than 2 seconds, and the steady state error is approximately zero. Steady state error is the discrepancy between the actual angle at steady state (state at which response does not change again) and desired angle at steady state (zero in this case).

Below in figure 13 are the results of a constant lateral slope.

![Figure 13: Lateral Test Results [2]](image)

From the figures above the approach of both roll and pitch to steady state are relatively quick at less than 2 seconds, and the steady state error is approximately zero.

For the dynamically varying test there was a plus or minus one percent error throughout the entire test, which is much better than other control attempts. The performance of the HOSM controller presented in this paper compared to other open loop and closed loop attempts are
shown below in figure 14.

<table>
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<tr>
<th>Reference</th>
<th>Log</th>
<th>Ground slope</th>
<th>Control method</th>
<th>Experiment</th>
<th>Leveling error</th>
<th>Percent error</th>
</tr>
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<tr>
<td>[8]</td>
<td>A</td>
<td>+22°</td>
<td>PID</td>
<td>Q.S.</td>
<td>+2°</td>
<td>9.1%</td>
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<tr>
<td>[19]</td>
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<td>GEO</td>
<td>Dyn.</td>
<td>+3°, +15°</td>
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<tr>
<td>[20]</td>
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<td>+22°</td>
<td>PID</td>
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<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>[21]</td>
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<td>+10°</td>
<td>PID</td>
<td>Dyn.</td>
<td>+4°</td>
<td>40.0%</td>
</tr>
<tr>
<td>Ours</td>
<td>P</td>
<td>±18°</td>
<td>HOSM</td>
<td>Dyn.</td>
<td>±1°</td>
<td>5.5%</td>
</tr>
</tbody>
</table>

Figure 14: Comparison to Other Control Systems [2]

Conclusion

The main contribution of this Honors Project is the implementation and testing of a High Order Sliding Mode controller that was designed for a four-legged robot. The system was able to address time independent inclinations in both uphill and lateral modes. With the lateral modes, even though time was not a major concern, the response to large inclines was still quick at less than 2 seconds. The steady state error was almost zero. The results were the same for the uphill inclination.

With the dynamic test, there was a light decrease in accuracy (+ or – one percent), but this was expected because of limitations of the linear actuators, not the control system itself, which is exactly what occurred. The error of the system was much lower than the other previous attempts made by researchers. The reason that the error was lower than the previous open loop attempt is because open loop controllers do not correct for error. The reason that the controller performed better than previous closed loop attempt is because those attempts used PID control, which is only suitable for linear systems. As discussed previously, the system is non-linear, so a HOSM controller was used. This technology will be useful for implementation in rovers with legs and wheels to provide both robust leveling and high speed.
References

1. Nasa Content Administrator, “MER: Mars Exploration Rovers”,
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