DESIGN, ANALYSIS, AND MANUFACTURING OF A HARDWARE-IN-THE-LOOP (HIL) SIMULATION FOR THE MODELING OF AN AUTONOMOUS TRACTION CONTROL APPARATUS

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ABSTRACT

Interplanetary Exploration has been a big part of NASA’s curiosity into exploring what is beyond our atmosphere and these goals are represented in their Strategic Plan to advance aeronautics and space exploration. The exploration of Mars has been in the forefront of such recent explorations with the mapping and surface sample retrieval so that mankind can more understand the planet. To propel this exploration, rover autonomy is a very crucial technology with much room for continuing improvements in the precision of all actions. While actions of previous rover designs are completely autonomous, they rely on cameras, GPS mapping, and algorithms used to guide the navigation system with a set of heuristics when encountering obstacles. There are many reasons for improving this system. For instance, in denser terrain, a clear path may not exist in the camera’s view; therefore, the rover will have to rely on a map obtained from a mosaic of images. However, a map used to traverse Martian terrain is not always available, in fact, new mapping of the Martian landscape is crucial to the exploration of the planet. Also, a set of heuristics may lead to iterative guesswork making the vehicle overcompensate for the maneuvering of the vehicle around obstacles, which will cause more misdirection. In this project, a completely autonomous differential and Traction Control Apparatus will be simulated by modeling the drive train of a rover using the pseudo-inverse of matrices and demonstrating the simulation with the use of electrical circuit representation. The modeling will justify the use of four wheels propelling the rover over harsh terrain as opposed to the use of a track style of traction. The mathematical modeling will show how the power supplied to each of the four wheels will be divided amongst the wheels in the case of any wheel slippage caused by harsh terrain or other obstacles that the rover will encounter. The electrical circuitry will follow the same rules as the mathematical modeling to demonstrate the dispersion of torque supplied to the wheels. The results of this research will help to develop software that will create a differential for an autonomous rover that would be free of iterative trial and error positioning when encountering obstacle and terrain produced wheel slippage.

INTRODUCTION

The word autonomy originates from the Greek word autonomia, which breaks down to the prefix auto-, meaning “self”, and the root -nomous meaning “law”. In space exploration, an autonomous space craft might make certain decisions for itself based on imagery observation and a pre-programmed algorithm that will determine the only possible logical outcome and then perform that task without having to ask controllers types of parameters (Wikipedia, 2014). This type of self-governing proves to be very useful in space exploration when man can’t always be in control of the exploring vehicles. For example, the exploration of Mars is heavily reliant on
autonomous vehicles. For one, it is extremely far from earth and would take a great deal of time to send a human that could explore, and another reason, would be the lack of previous mapping of the terrain. An exploration vehicle would need to be able to make adjustments, directional decisions, and mapping with little or no help from human intervention. The search for samples of Martian terrain is also one of the highest importance in exploring the planet. According to NASA scientists, to streamline the search for, the acquisition, and the retrieval of samples, rover autonomy is a crucial technology (Weisbin, Rodriguez, Schenker, Das, Hayati, Baumgartner, 1999). NASA desires to free itself of the arduous task of having mission controllers preplan every minute action of planetary explorers. A rover crawling a few meters per day across the surface of Mars, based on painstaking path planning by Earth-bound experts, reduces scientific discovery to a trickle. Far greater science output could be achieved if missions could capitalize on the range capabilities of a self-directed rover (Whalley, Freed, Takahashi, Christian, Patterson-Hine, Schulein, Harris, 2003).

After researching many different autonomous robotic projects, conclusions were made that navigational and differential systems of autonomous robots depended upon cameras, sensors, and lasers to help guide the vehicles so that a set of algorithms or heuristics could be used to guide them through unknown or hazardous terrain. One researched project states: The composite array of the ultrasonic and infrared sensors is researched and designed to expand the scope of the robot detection. A novel approach of multi-sensor information fusion based on the neural networks and the fuzzy control is presented. A BP neural network is used to fuse the information from multi-sensor so that the uncertainty of the sensors' information can be decreased and high accuracy of obstacle identification can be obtained (Changhong, Fanling, Shunxiang, Xu, Zhiteng, 2009). This study had shown how the use of multi-sensor information was used in conjunction with a BP neural network to guide the rover. The neural network being a set of rules used to guide the vehicle when an obstacle has been detected. Another project that was researched used an obstacle course that was already mapped. This project states: We have developed map recognition algorithm for recognizing the floor plan and high level multi-sensor topological navigation system utilizing the information to perform navigation tasks. In our algorithm, robot can recognize the floor plan to get enough information automatically like human. First, it recognizes the floor plan map, generates the path to destination and extracts two kinds of landmarks location from floor plan map. One is room plate landmark and the other is passage corner landmark. Second, these landmarks can be detected by camera and ultrasonic sensor in experimental environment. Robot can then navigate to the destination by following these landmarks and generated path (Ching-Chung, Luo, Yu-Chih, 2010). Mapping of environments is crucial in autonomous robotics. In another study, the mapping of indoor environments was used to guide vehicles. This project stated: Digital 3D models of the environment are needed in rescue and inspection robotics, facility managements and architecture. This paper presents an automatic system for gaging and digitalization of 3D indoor environments (Surmann, Nuchter, Hertzberg, 2003).

To help solve the problem of mapping and creating heuristics to provide the autonomy of exploration rovers, my mentor proposed an idea to create an autonomous differential capable of redistributing the torque applied to the wheels of such a robot. This idea originated as a mathematical model that would be used to demonstrate the redistribution using electrical circuitry. The plan was to use a pseudo-inverse of a 3x4 matrix. The three rows of the matrix represented the forward/backward motion, the side to side motion, and the third row represented
the torque applied to the wheels. The four columns represented the four wheels that would be supplied the power that was distributed. This would mathematically demonstrate the redistribution of power amongst the wheels. If one of the wheels started to slip, causing the rover to veer off course, the redistribution of power would supply the power to the other wheels so that the rover would continue the intended path. This redistribution would be the exact amount of power needed to keep the rover on course without the need for iterative heuristics. In other projects, if the vehicle veered off course, a set of heuristics would set the vehicle back in the other direction. The problem with this solution is the guesswork of how far the vehicle would need to be righted. If the algorithmic iterations sent the vehicle too far in the wrong direction, it would again need to be righted, and so forth. With the solution that my mentor provided, the correct amount of power would be redistributed every time the vehicle veered off course.

A problem faced with finding the solution for the matrix described is that there are only three equations in the matrix representing the motion of the vehicle with four columns representing the wheels that the power will be distributed amongst. The problem is that this matrix is unsolvable because it is not a square matrix. For this solution, as stated above, a pseudo-inverse would have to be used. In mathematics, a pseudo-inverse is a generalization of the inverse matrix. The most widely known type of pseudo-inverse is the Moore-Penrose Pseudo-inverse, which was independently described by E.H. Moore in 1920 and Roger Penrose in 1955. A common use of the Moore-Penrose pseudo-inverse is to compute a ‘best fit’ solution to a system of linear equations that lacks a unique solution (Wikipedia 2014). This solution would prove to be perfect for our equations since there is not a unique solution to the equations. There could be an infinite amount of solutions, since the power could be redistributed to the wheels in an unlimited amount of solutions, however, using the pseudo-inverse, the ‘best fit’ solution would be found, making our solution optimal.

The electrical circuit analysis is a way of demonstrating the effect of the redistributing power of the pseudo-inverse. This would physically show that when resistor is either too high or too low, the power would be redistributed to the other resistors. This could be shown using a Wheatstone Bridge (Figure 1) style of circuit which represented the four wheel drive rover with voltage supplies in both the x as well as the y direction of motion. To demonstrate the difference between four wheel drive as opposed to tracks for propelling the rover, a simple two resistor circuit in parallel (Figure 2) was used with a single power supply to demonstrate the two tracks that would be redistributing power.

Figure 1: Shows the Wheatstone Bridge circuit representing the four wheel drive rover.
EXPERIMENTAL METHODS

First a diagram of the variables used in the mathematical and circuit modeling was formed (Figure 3). The first matrix shows the force of the wheels which will be solved by the equations of the pseudo-inverse. The next is the directions the equations are written for with the rover. Force in the x and y directions, and torque applied to the wheels. The third is the directional variables of the circuit. Voltage in the x and y directions, and for the simplicity of the math in the circuit, the torque will be equal to zero.

\[
\begin{bmatrix}
F_1 \\
F_2 \\
F_3 \\
F_4 \\
\end{bmatrix}
\begin{bmatrix}
F_x \\
F_y \\
t_x \\
0 \\
\end{bmatrix}
\begin{bmatrix}
V_x \\
V_y \\
0 \\
0 \\
\end{bmatrix}
\]

Figure 3: Shows the variables used in the mathematical and circuit modeling.

Next, a diagram of the equations used in the pseudo-inverse was formulated (Figure 4). These two equations have been set in matrix form, and represent the circuit modeling for the Wheatstone Bridge circuit. The W matrix is the identity matrix with each resistor representing one of the wheels of the robot. The A matrix represents the equations of motion with each wheel at a 45 degree angle from the center of mass of the robot.

\[
W = \begin{bmatrix}
R_1 & 0 & 0 & 0 \\
0 & R_2 & 0 & 0 \\
0 & 0 & R_3 & 0 \\
0 & 0 & 0 & R_4 \\
\end{bmatrix}
A = \begin{bmatrix}
-\sqrt{2}/2 & \sqrt{2}/2 & -\sqrt{2}/2 & \sqrt{2}/2 \\
-\sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2 \\
\sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2 \\
\sqrt{2}/2 & -\sqrt{2}/2 & -\sqrt{2}/2 & \sqrt{2}/2 \\
\end{bmatrix}
\]

Figure 4: Shows the equations used in the pseudo-inverse.
Next, (Figure 5) is a schematic drawing of the Wheatstone Bridge circuit with the four resistors representing the wheels of the rover, and the two power supplies representing the x and y directions of the rover with the torque being represented by the power traveling through the circuit. These diagrams show the relation between the two models, and how solving the power redistributed through the resistors will relate to the wheels of the robot.

**Figure 5:** Shows the Wheatstone Bridge circuit representing the four wheels of the rover.

Using a method called Superposition, the current running through the circuit can be solved. Current in the x direction is basically side to side motion, while current in the y direction is forward and reverse. Again, for the circuit, the torque supplied to the wheels is placed at zero for the simplicity of the math (Figure 6).

\[
\begin{align*}
    i_x &= \frac{V_x}{R_1R_4 + R_2R_3 - R_1 + R_4} \\
    i_y &= \frac{V_y}{R_1R_2 + R_3R_4 - R_1 + R_2}
\end{align*}
\]

**Figure 6:** Shows the current running through the resistors solved using Superposition.

Next, a mathematical solution to the pseudoinverse when applying the force of the wheel matrix \(F_w\) through the identity matrix was found (Figure 7). Maple was used to formulate the solutions and represent the ‘best fit’ solution for the equations.

\[
\begin{align*}
    F_{ww} &= A^# F_b = \\
    &= \begin{bmatrix}
        \sqrt{2} & R_1(-V_xR_2R_4 - V_xR_3R_4 + V_yR_2R_3 + V_yR_2R_4) \\
        2 & R_1R_2R_4 + R_1R_3R_4 + R_1R_2R_3 + R_2R_3R_4 \\
        \sqrt{2} & R_2(V_xR_1R_3 + V_xR_3R_4 + V_yR_1R_3 + V_yR_1R_4) \\
        2 & R_1R_2R_4 + R_1R_3R_4 + R_1R_2R_3 + R_2R_3R_4 \\
        \sqrt{2} & R_3(-V_xR_1R_2 - V_xR_2R_4 + V_yR_1R_4 + V_yR_2R_4) \\
        2 & R_1R_2R_4 + R_1R_3R_4 + R_1R_2R_3 + R_2R_3R_4 \\
        \sqrt{2} & R_4(V_xR_1R_2 + V_xR_1R_3 + V_yR_1R_3 + V_yR_2R_3) \\
        2 & R_1R_2R_4 + R_1R_3R_4 + R_1R_2R_3 + R_2R_3R_4
    \end{bmatrix}
\]

**Figure 7:** Shows the solution to the pseudo-inverse using Maple.
Next, a solution for the voltage through the circuit was put through the pseudo-inverse (Figure 8). This was solved for the voltages of each resistor in terms of the resistance and the current in the x and y directions.

\[
\vec{V} = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} (R_1)(-i_{x,1} + i_{y,1}) \\ (R_2)(i_{x,2} + i_{y,2}) \\ (R_3)(-i_{x,3} + i_{y,3}) \\ (R_4)(i_{x,4} + i_{y,4}) \end{bmatrix} = \begin{bmatrix} R_1 \left(-V_x R_2 R_4 - V_x R_3 R_4 + V_y R_2 R_3 + V_y R_2 R_4\right) \\ R_1 R_2 R_4 + R_1 R_3 R_4 + R_1 R_2 R_3 + R_2 R_3 R_4 \\ R_2 \left(V_x R_1 R_3 + V_x R_3 R_4 + V_y R_1 R_3 + V_y R_1 R_4\right) \\ R_1 R_2 R_4 + R_1 R_3 R_4 + R_1 R_2 R_3 + R_2 R_3 R_4 \\ R_3 \left(-V_x R_1 R_2 - V_x R_2 R_4 + V_y R_1 R_4 + V_y R_2 R_4\right) \\ R_1 R_2 R_4 + R_1 R_3 R_4 + R_1 R_2 R_3 + R_2 R_3 R_4 \\ R_4 \left(V_x R_1 R_2 + V_y R_1 R_3 + V_y R_1 R_4\right) \\ R_1 R_2 R_4 + R_1 R_3 R_4 + R_1 R_2 R_3 + R_2 R_3 R_4 \end{bmatrix}
\]

**Figure 8:** Shows the voltage solution for the Wheatstone Bridge circuit using the pseudo-inverse.

Next, the rover was subjected to a comparison of four wheel drive differentiation to a differential using tracks. For this, the same procedure was used; however, the matrix used in the mathematical representation has been changed to a 1x2 matrix. The two equations represented the two tracks, while the one variable solved was the power supplied to the tracks. The circuit modeling used for this representation was a simple two resistor circuit in parallel with a single power source. The circuit could easily be solved with a current divider to show the distribution of current throughout the circuit (Figure 9).

\[
i_1 = \frac{R_2 i_0}{(R_1 + R_2)} \quad i_2 = \frac{R_1 i_0}{(R_1 + R_2)}
\]

**Figure 9:** Shows the two resistors in parallel representing the two tracks with the single power source. Below, the current at each resistor is solved using a current divider.
When comparing the mathematical modeling to the wheels of the rover, we must use the definition of the dot product showing the angle between the two solutions is equal to zero. This is used to show that the two results are parallel and only differ by a constant (Figure 10).

\[ \theta = \cos^{-1}\left( \frac{\vec{F}_W \cdot \vec{V}}{|\vec{F}_W| |\vec{V}|} \right) = 0 \]

Figure 10: Shows that when using the definition of the dot product, the angle between the two solutions is equal to zero, meaning they are parallel, and differ only by a constant.

DATA AND RESULTS

In each case, whether it being the tracks, or the four wheels, when one wheel or track starts to slip, the force distribution is weighted equally. In the case of the tracks, when one starts to slip, a negative amount of force is supplied to the slipping track, and an equally positive amount of force is supplied to the other track to keep the vehicle travelling in the intended direction. This is also true for the case of the four wheel driven rover, except the force is distributed among all of the other wheels when one starts to slip. The same holds true when more than one wheel slips, the force is distributed to the other remaining wheels. A mathematical representation is easily shown (Figure 11).

\[ \begin{bmatrix} R_1 \\ R_2 \end{bmatrix} = A^*F + [I - AA^*]z = \begin{bmatrix} 50 \\ 50 \end{bmatrix} + \begin{bmatrix} -1 \\ 1 \end{bmatrix}z \]

Where: \( A^*F \) = solution, \( z \) = any infinite amount

\[ [I - AA^*] = \text{projection onto the null space} \]

\[ \begin{bmatrix} R_1 \\ R_2 \end{bmatrix} = \text{Force value of each track} \]

Figure 11: Shows the mathematical representation of the solution to the wheel distribution of the rover with the tracks.

This is a closed form analytical solution to the distribution of power, and is the same type of solution for the four wheel drive version of the rover. The only difference would show the distribution of power across four different resistors. The \( A^*F \) is the pseudo-inverse solution that should be the ‘best fit’ solution, added to the projection onto the null space multiplied by any infinite amount of power denoted as \( z \). The solution is basically an equal distribution plus a negative amount of power added to the slipping wheel with the positive amount redistributed amongst the other wheels or tracks.

In the simulation, the Null Space is what gives the availability to use or conserve the energy that is being supplied to the wheels or tracks. This would give the general solution to the distribution of power to the drive elements whether they are tracks or wheels. This solution, however, is only the general case. The true solution uses the weighted pseudo-inverse which
takes into account for the weight distribution across the rover. The general solution is used in a case that has the rover’s weight equally distributed and completely square. The weighted solution takes into account the center of mass of the rover. This variable can also change depending upon the weight distribution of the payload. For this, traction coefficients are calculated to provide the correct weighted pseudo-inverse of the vehicle.

When finally deciding between using the tracks or the four wheels, the two are very similar as far as solutions. Both have infinite amount of solutions, but the tracks can be used to explain the power distribution much easier. In the mathematical modeling, the 3x4 matrix has a higher rank since it does have more equations and variables; however, it cannot be said it would be more useful since both setups have an infinite amount of solutions. Therefore, the choice came down to the maneuverability of the rover with each. The rover could perform much better with the four wheels, and with the Meccanum wheels chosen, the rover could move in a completely sideways motion that the tracks could not perform.

CONCLUSIONS AND FUTURE RESEARCH

The research and experimentation provided was meant to advance the actions of autonomous vehicles. With the use of the pseudo-inverse differential, an autonomous vehicle can perform more precisely without using iterative heuristics or human intervention. From this technology, it would be beneficial to vehicles travelling in unexplored terrain. The vehicle would not be dependent upon pre-existing maps and images, and could actually help to make new maps of foreign terrain. This would be very beneficial to NASA in their quest to study new planets such as Mars.

From this research, a four wheel drive differential is just as beneficial using the Hardware-In-the-Loop (HIL) technology as a track driven system; however, four wheel drive is much more maneuverable than a track driven system. This can also help propel future projects from having to make the same decision.

Future projects and research will involve writing software that is capable of running the HIL simulation on a rover that has already been built. The rover is equipped with meccanum wheels, and is capable of rewriting the software that it already is using to control it manually. Implementation of the HIL software will be the last procedure in manufacturing a completely functioning autonomous traction control apparatus (ATCA) that is run using the HIL simulation.
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