Understanding Failure Modes of Unmannered Ground Vehicles (UGVs)

Author: Joshua Titus

Advisors: Prof. Dawn Tilbury
Prof. Galip Ulsoy

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Abstract:

To better understand the failure modes of unmanned ground vehicles (UGVs), it is often helpful to use simulations instead of physical testing, especially when the actual UGV that is being evaluated is not available. This was the case during my project, as the PackBot has yet to be delivered to the University of Michigan at the date of this publication. Performance modeling of PackBot has previously been accomplished and has been published [1,2,3,4]. Thus, the purpose of my project is to model the performance of the PackBot under different failure modes. To do this, the performance of PackBot is given a rating based on its performance on various courses with respect to the nominal vehicle performance. The goal is to understand how different failure modes affect performance, and more importantly, which ones lead to critical failures and how to prevent them.
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1 Overview

The main focus areas of my research were creating a CAD model, analyzing the CAD model with dynamic simulation software (Adams) to discover failure mode effects, setting up an issue tracker for the PackBot and talking with repair technicians at the Selfridge repair facility about reliability issues with UGVs. Each of these four areas are discussed in greater detail in their respective sections. Additional information on important contacts and information on reliability testing methods used at TARDEC can be found in the additional Appendices D and E. Account Information for the IFS space, MySQL server and Mantis PHP page can be found in the additional Appendix F.

2 CAD Model

The CAD model is the basic structure that I will use for the dynamic simulation. Once the CAD model is complete and put into an assembly, this file can be imported into Adams and used to create the initial geometry that will be used for testing. This is useful because Adams has limited CAD capabilities, and thus more complicated geometries can be created in CAD and then imported into Adams to create a more accurate simulation model. Detailed CAD drawings of the PackBot and Testing Platform can be found in Appendices A and B.

2.1 Model Description

More accurate dimensions were obtained from Selfridge (physical measurements of device, original notes and dimensioned drawings can be found on the RA4 Ctools Site) to create a rough model of the PackBot. A detailed CAD model of the PackBot was not available at the time, so by using the dimensions we have the goal is to get a roughly similar shape the PackBot. However, the final results will not directly correlate to actual PackBot performance, since the model will only be an approximation at best. Therefore, the results from this model are qualitative, and measure performance effects of various failure modes when compared to nominal UGV operation.

The CAD model of the PackBot used for my simulations looks as shown in Figure 1. This model has the two 24V batteries attached at both sides just in front of the rear drive wheels (battery dimensions are currently estimates, since actual dimensions were not taken). The main control unit is in the front of the UGV, however, the arm has been left off for this analysis (future simulations could easily include the arm). Also, the PackBot was modeled using wheels rather than tracks for simplicity and because Adams has difficulties modeling track dynamics. Full dimensions of the PackBot can be found in Appendix A.
Figure 1: PackBot UGV CAD Model

The weights of various parts of the PackBot were measured while at the Selfridge repair facility, however, distribution of weight (center of mass) measurement was not possible. Therefore, I estimated the density of each component to meet the total weight value of that piece, which assumes uniform density throughout each part. This is a rough approximation and could be improved in the future with better density values, dimensions (CAD) and center of mass measurements. Total actual measured PackBot weight with two batteries and no arm was 19 Kg, which is very close to the model 19.28 Kg.

PackBot Model Weight Information:

- **Main Body:** 1.10E-006 Kg/mm³ results in 10.28 Kg total
- **Wheels:** 1.25E-006 Kg/mm³ results in 1.00 Kg per wheel, 4.00 Kg total
- **Batteries:** 2.10E-006 Kg/mm³ results in 2.50 Kg per Battery, 5.00 Kg total
- **Total Weight:** 19.28 Kg

The test platform used for my simulations was also created with CAD and then imported into Adams. The platform is shown in Figure 2, and incorporates both testing conditions that I used for my simulations (stairs/ramp). The stairs were created using standard ergonomic dimensions for commercial stair applications, with a step height of 180 mm and a step landing of 280 mm. The ramp was given a radius of approximately 5 times the length of the PackBot to allow for a gentle enough slope for testing. In the future, it may be beneficial to decrease the slope even further to provide greater differentiation in ramp climbing distance since the PackBot Model did not make it up the ramp very far. Full dimensions of the testing platform can be found in Appendix B.
3 Simulation Results (Adams)

The simulation results were obtained by running the Adams model numerous times over the two different terrains with various failure modes. Detailed results from my testing are discussed in the following sections. It should be noted that these tests were done without the attached arm, tracks, flippers or other payloads. These additional items will change the dynamics of the vehicle and therefore the results of any future tests that include/exclude them.

3.1 Objective

My goal is to create an Adams simulation model to test the various failure modes of UGVs. The simulation will assess the dynamic capabilities of a PackBot type robot (my rough PackBot model). The dynamic model was used to simulate failures by removing various parts and then testing the PackBot’s ability to complete tasks (ramp/stairs) in this state (i.e. complete failure, limited mobility, etc.). The performance under these various failure modes will be compared to the performance of the nominal vehicle, thus allowing for a relative comparison of performance (not an absolute performance metric). Relative performance comparisons should be more robust to small differences in weight distribution or dimensions between my current PackBot model and the actual PackBot values. Therefore, the relations found in my testing should still hold for the actual PackBot and other similar UGVs in general.

3.2 Simulation Description

The duration of the simulations was 5 seconds, with 100 time steps (each time step was 0.05 of a second). This was of sufficient duration to allow the model to complete the simulation and also at a small enough step size to get good resolution on the dynamics of the model.
To simulate the contact between the PackBot and the test surface, a standard coulomb friction model was used with a static friction coefficient of 0.3 and a dynamic coefficient of 0.1 for all tests. These values can be modified in the future to increase the accuracy of the model or to adjust for varying terrains.

The torque to each wheel was 760 N/mm for all tests, except for the increased torque test where the right drive wheel was increased by 20% to 912 N/mm. These values proved to give good results for my simulations for both the stairs and the ramp.

For further details on specific test conditions, reference the original test files provided on the Ctools GRRC RA4 page in the folder “Josh’s Research/Adams”.

3.3 Results

Using the testing platform, two separate sets of tests were run. The tests run on the stairs can be seen in Figure 3 (complete results in Appendix C), while the tests from the ramp can be seen in Figure 4 (complete results in Appendix C). For each test, 6 different conditions were used, one of them being the nominal fully functional condition and the remaining 5 were failure modes of the PackBot holding all other conditions constant. The first failure mode was the removal of the left battery to test how weight imbalance affected performance (simulation of it falling off or just not being used). The second failure mode was similar, however, it involved the removal of both batteries (testing the effects of weight on performance). The third failure mode was testing the effects of drive motor torque variation, specifically whether increasing the drive torque from one wheel will affect performance. The fourth failure mode was to test the effects of losing a front wheel on performance. Finally, the fifth failure mode was to test the impact of losing a drive wheel on vehicle performance.

Two plots are shown below from the simulations run. This is a sample of the results, for all graphs refer to Appendix C. Figure 3a is the nominal test case and Figure 3e is the test where the left front wheel is removed. The blue dotted line shows the position of the center of mass in the y-axis (vertical), the red line shows the position of the center of mass in the x-axis (horizontal), and the dark blue and pink lines show the acceleration of the center of mass. These graphs illustrate the differences between nominal operation and operation under a failure mode condition for the stair simulation. With the front left wheel removed, the PackBot travels slower and thus travels a much shorter distance in the x-axis. You can also see that the impact from traveling down the stairs was greater with the wheel removed by the higher spike in center of mass acceleration. For complete results and discussion, see Table 1.
There are a few special notes on the stair simulation testing. During the simulation with both batteries missing the PackBot almost flipped over as it descended the stairs. The lighter weight of the PackBot without the batteries appears to make it more susceptible to overturning in this test setup. Additionally, the PackBot did flip over during the simulation with the left front wheel removed. This is most likely caused by the front left edge getting caught on the stair because the wheel was missing.
Two plots are shown below from the simulations run. This is a sample of the results, for all graphs refer to Appendix C. Figure 4a is the nominal test case and Figure 4e is the test where the left front wheel is removed. The red line shows the position of the center of mass in the x-axis (horizontal), the blue dotted line shows the position of the center of mass in the y-axis (vertical), and the pink dotted line shows the position of the center of mass in the z-axis (across plane). These graphs illustrate the differences between nominal operation and operation under a failure mode condition for the ramp simulation.

Under nominal conditions, the PackBot reaches a higher height on the ramp and also travels farther along the ramp as shown by the higher peaks of the blue dotted and red lines. The pink dotted line also shows that with one wheel removed the vehicle does not travel in a straight line and will deviate from the intended path. Additionally, the position of the peaks indicates how long it takes to reach maximum height. From the plots, we can see that the PackBot without the wheel reached the maximum height well after the nominal case. For complete results and discussion, see Table 2.

![Figure 4a: Ramp Simulation Nominal](image-url)
One special note on the ramp simulation data; when both batteries were removed the PackBot performed very poorly. The back drive wheels spun and lost traction with the decreased weight and the vehicle was unstable going up the ramp (as shown by the curvy Z-position line) with the back end sliding from side to side. A similar problem arose with the increased torque on the right drive wheel; the right wheel spun freely while the left wheel remained in contact with the ramp. Surprisingly, even with the right wheel spinning freely the PackBot climbed the ramp the straightest of any of the other tests, including the nominal test case.

The test results from the stair simulation are summarized in Table 1, where time to fall, X-position travel and maximum acceleration are the three metrics used for comparison to the nominal performance. Time to fall is a measure of how long the vehicle remained on the stair platform before falling off. In the first 4 cases, this is a good comparison for indicating whether the vehicle fell off before it reached the end of the platform since all vehicles were operating at similar speeds. For the last 2 cases, the missing wheels significantly slowed down the vehicle and thus increased the time substantially. The X-position travel is an indicator of the horizontal speed of the vehicle over the stairs and shows the effect of various failure modes on the distance traveled during the 5 second simulation (and resulting velocity). The maximum acceleration of the vehicle indicates how well the vehicle travels over the stairs (how rough the impacts will be). This value seems to be influenced substantially by vehicle weight and velocity, thus, most of the test cases have better maximum acceleration values than the nominal case.
### Table 1: Stair Simulation Results

<table>
<thead>
<tr>
<th>Test</th>
<th>Time to Fall (sec)</th>
<th>% diff from Nominal</th>
<th>X-Position Travel (mm)</th>
<th>% diff from Nominal</th>
<th>Max Accel. (mm/sec²)</th>
<th>% diff from Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>4.00</td>
<td>NA</td>
<td>7250</td>
<td>NA</td>
<td>2.25E+06</td>
<td>NA</td>
</tr>
<tr>
<td>Left Battery Removed</td>
<td>3.88</td>
<td>-3</td>
<td>5500</td>
<td>-24</td>
<td>2.00E+06</td>
<td>-11</td>
</tr>
<tr>
<td>Both Batteries Removed</td>
<td>4.25</td>
<td>6</td>
<td>7000</td>
<td>-3</td>
<td>1.38E+06</td>
<td>-39</td>
</tr>
<tr>
<td>Right Higher Torque</td>
<td>4.13</td>
<td>3</td>
<td>6625</td>
<td>-9</td>
<td>1.88E+06</td>
<td>-16</td>
</tr>
<tr>
<td>Left Front Wheel Removed</td>
<td>5.00</td>
<td>25</td>
<td>6250</td>
<td>-14</td>
<td>2.38E+06</td>
<td>6</td>
</tr>
<tr>
<td>Rear Drive Wheel Removed</td>
<td>5.13</td>
<td>28</td>
<td>5500</td>
<td>-24</td>
<td>1.25E+06</td>
<td>-44</td>
</tr>
</tbody>
</table>

The results shown in the table illustrate a few key findings. The loss of a wheel, whether it is the front or rear, is the worst failure mode when traversing stairs. Losing a rear drive wheel (-24%) is slightly worse than losing a front wheel (-14%) when vehicle velocity is considered, however, on the stairs the missing front wheel caused the PackBot to flip over and completely incapacitated it (non-operable). This failure mode would completely end operations in the field and is a critical failure mode. Weight is very important and changes the acceleration forces experienced by the PackBot significantly. Thus, special precautions should be taken when operating the PackBot with 2+ batteries over uneven terrain, especially since the bottom plate on the housing is so close to the circuit board and other internal electronics. Weight also causes the PackBot to turn when traveling down stairs, as shown by the lowest time to fall (went off the side of the platform instead of the end).

The test results from the ramp simulation are summarized in Table 2, where the X-position distance, Y-position distance and Z-position drift are the three metrics used for comparison to the nominal performance. The X-position distance is a measure of the distance traveled into the ramp in the x-plane (horizontal). This value is measure from the beginning of the ramp to the farthest horizontal position reached. The Y-position distance is closely related and is a measure of the height reached when climbing the ramp (vertical). This value is measured from the starting platform to the highest vertical position reached. These two values are good indicators of climbing performance, and correlate well with each other. The Z-position drift is a measure of how well the vehicle climbs the ramp (how straight the climb is). If the PackBot slides to one side or the other this parameter will capture the deviation (it is the difference between max and min z-axis position during the simulation).
Table 2: Ramp Simulation Results

<table>
<thead>
<tr>
<th>Test</th>
<th>X-Position Dist. (mm)</th>
<th>% diff from Nominal</th>
<th>Y-Position Height (mm)</th>
<th>% diff from Nominal</th>
<th>Z-Position Drift (mm)</th>
<th>% diff from Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>661</td>
<td>NA</td>
<td>104</td>
<td>NA</td>
<td>20</td>
<td>NA</td>
</tr>
<tr>
<td>Left Battery Removed</td>
<td>677</td>
<td>2</td>
<td>108</td>
<td>4</td>
<td>48</td>
<td>140</td>
</tr>
<tr>
<td>Both Batteries Removed</td>
<td>419</td>
<td>-37</td>
<td>62</td>
<td>-40</td>
<td>73</td>
<td>265</td>
</tr>
<tr>
<td>Right Higher Torque</td>
<td>582</td>
<td>-12</td>
<td>86</td>
<td>-17</td>
<td>13</td>
<td>-35</td>
</tr>
<tr>
<td>Left Front Wheel Removed</td>
<td>488</td>
<td>-26</td>
<td>73</td>
<td>-30</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>Rear Drive Wheel Removed</td>
<td>426</td>
<td>-36</td>
<td>59</td>
<td>-43</td>
<td>104</td>
<td>420</td>
</tr>
</tbody>
</table>

The results in the table illustrate a few key findings. Decreasing weight results in better climbing performance up to a point. With one battery removed, the PackBot is able to climb 2% higher than the nominal case. However, with both batteries removed the vehicle actually climbs the ramp the worst of all the test cases (-37%). This is because the wheels spin without the added weight of the battery and cause the PackBot to slide back down. The best weight for the vehicle will be a function of the coefficients of friction used (operating terrain) and the placement of the given weight (and how it affects the center of gravity). The results also show that losing a wheel has a substantial impact on the PackBot’s ability to travel a straight path up a ramp, as shown by 400% and 420% difference from nominal from missing a front wheel and a rear wheel, respectively.

4 Issue Tracker (Mantis)

The issue tracker is a web-based (accessible from any computer) issue tracking database, for recording reliability related data for the PackBot robotic platform at the University of Michigan and Wayne State University. This issue tracking database is specifically set up for the PackBot, however, in the future can be used for numerous other projects as well. Specific information on the setup of the Mantis Issue Tracker, IFS space and MySQL can be found in the additional Appendix F.

4.1 Benefits and Capabilities

This program has a streamline design and intuitive user interface making it easy to use and simple to record our data. The Mantis software is also Global Public License (GPL, free) and also has an active development team that updates the software regularly with new features.
Other features include:

- Supports any platform that runs PHP (Windows, Linux, Mac, Solaris, AS400/i5, etc)
- Simple/Advanced Issue Pages
- Multiple Projects per instance
- Support for Projects, Sub-Projects, and Categories.
- Users can have a different access levels for access or per project
- Search and Filter
- Built-in Reporting (reports / graphs)
- Custom Fields
- Export to .csv, Microsoft Excel, Microsoft Word
- Authentication (access control)
- Full List can be found here: http://www.mantisbt.org/wiki/doku.php/mantisbt:features

4.2 How to Use

The Issue Tracker is based off the Mantis PHP software and is very user friendly. The menus are intuitive and in a short time you can get adjusted to the site layout. The main screen layout is shown in Figure 5, with important features pointed out out.

![Figure 5: Typical Main Screen Layout for Issue Tracker](image)

The main highlighted region shows an overview of the most recent issue activity. This is very useful for getting an idea of the problems being worked on currently. To get the complete list of issues you click on “View Issues” in the Top Toolbar. To report a new issue, just click on “Report Issue” in the Top Toolbar and select the appropriate project and details for the issue. If you need to change any of the account
privileges/access, add/delete/edit projects or make any other changes to the site you can get access to this area by clicking “Manage” in the Top Toolbar. If you only need to make changes to your account, this can be accessed from “My Account” in the Top Toolbar.

For further information related to technical issues please refer to the online help manual located at: [http://www.mantisbt.org/manual/](http://www.mantisbt.org/manual/) A hardcopy of the manual is also posted on the Issue Tracker website as an issue with an attachment.

5 UGV Repair Technician Insights

These are the combined notes taken by everyone that attended the JRRF/Selfridge visit on March 11th, 2009. The notes that specifically related to reliability issues are summarized and reproduced below with minor editing. The entire documentation of the visit can be found on the GRRC-RA4 Ctools site wiki page [5].

5.1 Talon Reliability

The connectors are a significant reliability problem on the Talon. They short out when too much current is passed through them. Also, even though the connectors are unidirectional plugs, people try to force them in the wrong way and have been known to connect them improperly. The arms and arm motors are also problematic on the Talon, and are the cause of many repair cases/issues [5].

5.2 PackBot Reliability

The main housing on the PackBot has only a 3/16" clearance between the bottom of the robot and the circuit boards. If the bottom panel gets dented (from running over rocks or other obstacles), there can be shorts and failures on the circuit board. Also, since the electric motors and circuit boards are inside the housing and it is waterproofed (no venting or fins), the whole enclosure can overheat, resulting in total robot failure. There is no temperature sensor/feedback to the operator to help mitigate this risk of overheating [5].

5.3 General UGV Reliability

Repairs in the field are done with a 4 hour turnaround time limit. If they cannot be completed within 4 hours, the team is given a new robot and the robot needing repair is shipped back for repair. Usually, field repair involves replacing a simple module, and thus is relatively quick. More involved repairs to the modules themselves are usually sent to a repair facility. Although field technicians can repair modules, it is not their primary function, so modules (e.g. arms, computers, etc.) are sent back to a central repair facility (Selfridge) for repair.

The military doesn’t do much, if any, preventative maintenance (PM). The robots are sent in for repair before any PM would be scheduled (very low MTBF). There is a tradeoff between weight and reliability/performance. To meet a goal of 35 lbs, iRobot had to remove the treads on the flippers among
other things. Without the treads, the flippers are not as useful for climbing obstacles or getting “unstuck” from tight places.

The typical robot purchase price is around $100K. Chief Stevens estimated that annual maintenance costs are approximately 20% of purchase price, or $20K per year for a typical robot. This figure illustrates why reliability improvement are such a high priority.

Common reliability issues mentioned by JRRF:

- **Fatigue/breaking of electronics** - due to vibration, harsh terrain, and heat (cameras hold up well)
- **Thermal problems** - due to packing of electronics in tight space in chassis, heat buildup under ballistic protection
- **Tearing of tracks** - due to wear and tear, especially at the region contacted by the drive wheel. Tracks are replaced several times over the lifetime of a robot.
- **Failure of arms** – especially failure due to the motors. The arm is often replaced entirely, with the broken arm sent to JRRF for repair

Chief Stevens commented that most failures are situational rather than fatigue/time-based. Unfortunately, there are no official "best practices" for operating a robot to improve reliability or performance. The military avoids even straightforward (simple) suggestions (e.g., stow the arms while traversing terrain to avoid excessive vibration) due to liability issues for individual personnel in the absence of military standards. Additionally, there is no MOS (Military Occupational Specialty = military job classification) for operating a robot. Robot operators generally have an engineering background but there isn’t a special classification for this position. Therefore, operators may not know the full functionality of the robot nor its limitations for safe operation which could lead to an increased number of situational failures as Chief Stevens pointed out.

The Army keeps an extensive database of robot maintenance records. This database is called COLTS. Chief Stevens is looking into providing training and access to the database for UM and TARDEC researchers. This process is ongoing, but once completed should give us access to extensive reliability data on UGVs in the field and help us better understand the reliability issues facing UGVs today [5].

6 Conclusions and Recommendations

Throughout all the tests and simulations, the common critical failure modes seem to be the loss of either the front or rear wheels and unbalance caused by missing batteries (and increased risk of damage from greater weight). This is not unexpected, and makes sense given that the PackBot is unbalanced without all four wheels to distribute the weight. Additionally, when the drive wheel is missing the vehicle also looses half its propulsion force, further unbalancing the vehicle. The batteries represent a significant portion of the PackBot weight and thus their placement, number and use affect the
performance of the vehicle substantially. Therefore, special care should be taken to avoid placement where they could cause greater imbalances or further reliability concerns.

In the future, the model used in this research should be updated with more accurate and detailed models of current commercial UGVs. With actual CAD models, the densities of each component could be used and the actual dynamic performance of the UGV could then be determined. Development of a tracked model would also be helpful given that the two most popular UGVs used commercially today rely on tracks for propulsion. In addition to this, better models for track/ground interactions need to be developed and used instead of standard coefficients of friction. This will help greatly to get a more accurate simulation of real world performance.

Finally, while I tested various failure modes individually, it would be beneficial to investigate the interactions of various failure modes. For instance, the combination of missing the right front wheel and the left battery would cause the vehicle to be more off balance than either failure mode alone, and this interaction and resulting performance effects could be very interesting. In the future, more failure modes could also be added to make the testing more complete.
7 References


Appendix A: PackBot Model Dimensions
Appendix B: Testing Platform Dimensions
10 Appendix C: Simulation Test Results

Figure 3a: Stair Simulation Nominal Run

Figure 3b: Stair Simulation Left Battery Removed
Figure 3c: Stair Simulation Both Batteries Removed

Figure 3d: Stair Simulation Right Side Higher Torque
Figure 3e: Stair Simulation Left Front Wheel Removed

Figure 3f: Stair Simulation Rear Drive Wheel Removed
Figure 4a: Ramp Simulation Nominal

Figure 4b: Ramp Simulation Left Battery Removed
Figure 4e: Ramp Simulation Left Front Wheel Removed

Figure 4f: Ramp Simulation Rear Drive Wheel Removed