

SIMULATION BASED ACCEPTANCE TESTING FOR UNMANNED GROUND VEHICLES

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ABSTRACT

Acceptance testing is considered a final stage of validation, and performing acceptance tests of an actual UGV system can be expensive and time-consuming. Therefore, this paper discusses simulation based acceptance testing for UGVs, which can significantly reduce the time and cost of the acceptance test. In this paper, both dynamic and static simulation models are developed, and the results from these simulations show that the static simulation can be used, rather than the more complex dynamic simulation, because of the slow operating speed of UGVs. This finding improves the development efficiently at the simulation model development phase. In addition, the developed simulation models provide a better understanding of the UGV failure modes. The static simulations can determine the required joint motor torques for various UGV loadings and maneuvers and provide data for the full range of operating motion. Specifically, given threshold joint torque value, the safe operating range of the two-link robot arm can be determined. A multi-body dynamics model of the iRobot Packbot was prepared in MSC ADAMS to simulate a full range of two-link manipulator operation. The static simulation model is implemented using MATLAB software.

INTRODUCTION

In 2004, the US army was using about 160 robots in Iraq and Afghanistan [8]. This number grew to approximately 4,000 in 2007 and continued to climb to about 6,000 in 2008. With the rapid increase of UGV usage in military operations, one primary concern of robotics researchers and users is UGV reliability. Studies of mobile robots used in Urban Search and Rescue (US&R) and Military Operations in Urban Terrain (MOUT) have shown a mean time between failures (MTBF) in the field of 6 to 20 hours, well below the desired 96 hours as established by Test and Evaluation Coordination Office (TECO), part of the Maneuver Support Center at Ft. Leonard Wood [6]. Some of the failures are due to manufacturing defects or subtle interactions between components, and these failures could be detected and prevented prior to the field deployment. However, other failures are due to uncertain environments, misuse by operators, and insufficient understanding of failure modes. Therefore, it is important to develop an acceptance test to provide better understanding of the failure modes and to ensure that such systems meet their reliability goals. Although such testing methods are widely used in various engineering applications, there is still no general guidance for UGV acceptance tests in terms of system reliability. Thus, the purpose of this paper is to suggest research ideas

that might provide a basis for development of an acceptance test for small UGVs or mobile robots.

Some of the earliest work on UGV reliability and acceptance testing was done by Robin R. Murphy and her collaborators [2-6]. Murphy discussed a methodology similar to a final factory acceptance test, i.e., a test usually performed by a manufacturer prior to shipping. In contrast, this paper discusses a methodology for simulation based acceptance testing in which simulations are used to identify the worst-case scenarios in UGV operations. There are two advantages to performing a simulation based test rather than actually testing a physical system. The first advantage is that simulations can significantly reduce the testing time and costs because performing multiple tests for a UGV system for failures can be expensive and time-consuming. Second, a simulation can provide results that are physically infeasible using destructive testing.

In this paper, as examples of the simulation-based approach, two common UGV failure cases are investigated: joint torque saturation and rollover. In order to determine worst-case scenarios during UGV operations, we examined both dynamic and static simulation models for the iRobot Packbot, a multi-mission tactical mobile robot. The paper is organized as follows. First, it discusses the related works in

UGV reliability and acceptance testing. Then it discusses the methodology for performing simulations to determine test scenarios, and the findings and discussion are given subsequently. The paper concludes with a brief discussion on future research directions.

BACKGROUND

This paper is intended to help users of UGVs to have a better understanding of failures modes and reliability. Therefore, it is important to evaluate possible failure modes and the reliability of the current UGV systems. In [4], a novel taxonomy of UGV failures is introduced which categorizes failures based on the source of failures, physical and human. Then physical failures are then categorized based on the common subsystems in UGV platforms: effector, sensor, control system, power, and communications. Human failures are subdivided into design and human interaction. The taxonomy of UGV failures are shown in Figure 1.

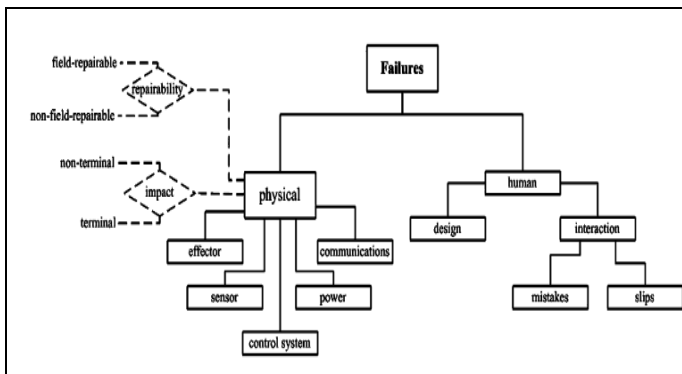


Figure 1: The taxonomy of UGV failures

The previous work by the Center for Robot Assisted Search and Rescue (CRASAR) includes 13 studies and 15 different models of field robots in USAR or military operations [2][3]. This study showed that an overall MTBF of 8 hours and an availability of less than 50%. The effectors were the most common type of failures, 39% of overall failures, and the control system was the next with 29%.

In order to ensure that field robots meet such performance requirements and reliability targets, it is important to develop an acceptance test and performance testing standards for UGVs. Some preliminary work on UGV acceptance testing has been done by Robin R. Murphy and her collaborators. In [6], the role of endurance testing for rescue and safety robots is discussed. It describes a methodology for endurance testing recommended for a certain class of robots. A six-hour endurance test was developed for a commercially available rescue robot. The test uncovered failures under certain conditions and the

source of the failures. In addition, the test data identified key design and manufacturing issues.

In terms of performance standards, the Department of Homeland Security initiated an effort in 2004 to develop performance standards for Urban Search and Rescue (US&R) robots [1]. In order to ensure that applicable technologies are relatively easy to use and to integrate efficiently into existing systems, standardized test methods were needed. Therefore, the Department of Homeland Security Science and Technology Directorate initiated an effort in 2004 with NIST to develop comprehensive standards to support development, testing, and certification of effective robotic technologies for USAR applications. These standards address robot mobility, sensing, navigation, and human system interaction. However, these standards have focused on functionality and verifying system capabilities. Therefore, this paper investigates simulation based acceptance testing to provide a faster and easier method to develop performance testing and to determine robot reliability.

METHODOLOGY

Acceptance tests play an important role in the verification and demonstration of key performance requirements and system reliability of UGVs. In order to establish an acceptance test, the essential performance requirements and efficient test scenarios for each of the performance requirements need to be determined. These test scenarios emulate UGV operations and user environments, and ensure that the system meets the performance requirements and reliability goals. In this paper, we used simulation to develop the test scenarios for two common UGV failures: joint torque saturation and rollover failures. The system used in the simulation is the iRobot Packbot with Explosive Ordinance Disposal (EOD) kit. First, a dynamic simulation model is developed because the system consists of many moving parts. Next, a static simulation model is developed and compared to dynamic simulation model. Statistical testing is used to confirm that the static simulation can be an alternative to the more complex dynamic simulation model under a certain operating speed range. The paper also shows how the methodology can be applied to identify the test ranges for joint torque saturation and rollover failures.

Dynamic Simulation

In multi-body dynamic simulation, all the components are modeled in a CAD system and converted into rigid bodies for use in multi-body dynamic simulation software. The model used for the analysis has the dimensions $L_1=0.55m$, $L_2=0.64m$, $m_1=2.5kg$, $m_2=2.5kg$, and $m_L=4kg$, and this is based on the measurements taken from an actual iRobot Packbot manipulator (Explosive Ordinance Disposal (EOD)

kit). The Free Body Diagram (FBD) of a two-link planar robot arm is shown in Figure 2.

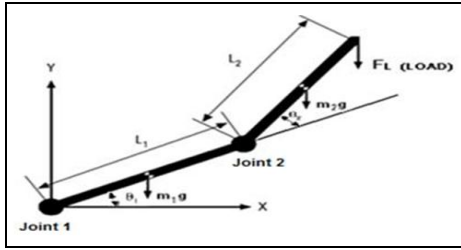


Figure 2: Free Body Diagram of a Two-link Robot Arm

The original tracked platform is simplified to four wheels, and the manipulator is also simplified to two-links without a gripper. After all the parts are assembled, the complete model is exported as a parasolid format to make the file compatible with the MSC ADAMS software package. The simulation calculates information such as lateral and longitudinal forces, torques, angular velocity and acceleration at each joint. The model also accounts for all center of gravity locations in each component. The model will be validated in future research with data for comparable mobile robots. Figure 3 shows the 3-D graphical rendering of the vehicle model in the “closed-in” position and the “manipulator extended” position.

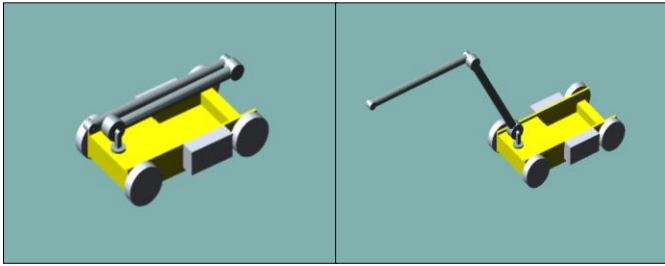


Figure 3: Multi-body dynamic simulation model in the “closed-in” position and the “manipulator extended” position

Static Simulation

Consider a system consisting of a wheeled platform and a two-link planar robot arm as shown in Figure 3. It is desired to drive each arm by a separate joint motor due to ease of position control from a control logic viewpoint. The required joint torque to maintain arms in a certain position is merely the reaction moments at each joint. Solving for the reaction moments, or required joint torque, results in the following relations,

$$\tau_1 = \left(m_1 g \frac{L_1}{2} + m_2 g L_1 + F_L L_1 \right) \cos(\theta_1) + \left(m_2 g \frac{L_2}{2} + F_L L_2 \right) \cos(\theta_1 + \theta_2) \quad (1)$$

$$\tau_2 = \left(m_2 g \frac{L_2}{2} + F_L L_2 \right) \cos(\theta_1 + \theta_2) \quad (2)$$

Equation (1) defines the reaction moment at the first joint, and Equation (2) defines the reaction moment at the second joint. If θ_1 is given, τ_1 and τ_2 have maximum and minimum values when $\frac{d\tau_1}{d\theta_2}$ and $\frac{d\tau_2}{d\theta_2}$ are equal to zero.

$$\frac{d\tau_1}{d\theta_2} = \frac{d\tau_2}{d\theta_2} = - \left(m_2 g \frac{L_2}{2} + F_L L_2 \right) \sin(\theta_1 + \theta_2) = 0 \quad (3)$$

As we can see from the equation above, the maxima and minima for both τ_1 and τ_2 are observed at the same orientation of the robot arm. By solving Equation (3), we can conclude that at the worst-case orientations, the second joint angle is determined as $\theta_2 = 2\pi - \theta_1$ if $0 < \theta_1 < \pi/2$ and $\theta_2 = \pi - \theta_1$ if $\pi/2 < \theta_1 < \pi$. Given the first joint angle, the second joint angles at the joint torque absolute maxima are shown in the Table 1.

First Joint Angle (Radian)	Second Joint Angle (Radian)	Manipulator Orientation
0	0, 2π	
$\pi/6$	$11\pi/6$	
$\pi/3$	$5\pi/3$	
$\pi/2$	$\pi/2, 3\pi/2$	
$2\pi/3$	$\pi/3$	
$5\pi/6$	$\pi/6$	
π	0, 2π	

Table 1: Given the first joint angle, the second joint angle at the joint torque absolute maxima are determined

By setting the joint torque thresholds T_1 and T_2 , the safe working range of the second joint can be determined under the given first joint angle range of $0 < \theta_1 < \pi/2$.

$$T_1 \geq \tau_1, T_2 \geq \tau_2 \quad (4)$$

$$T_1 \geq \left(m_1 g \frac{L_1}{2} + m_2 g L_1 + F_L L_1 \right) \cos(\theta_1) + \left(m_2 g \frac{L_2}{2} + F_L L_2 \right) \cos(\theta_1 + \theta_2) \quad (5)$$

$$\cos(\theta_1 + \theta_2) \leq \frac{T_1 - \left(m_1 g \frac{L_1}{2} + m_2 g L_1 + F_L L_1 \right) \cos(\theta_1)}{\left(m_2 g \frac{L_2}{2} + F_L L_2 \right)} \quad (6)$$

$$T_2 \geq \left(m_2 g \frac{L_2}{2} + F_L L_2 \right) \cos(\theta_1 + \theta_2) \quad (7)$$

$$\cos(\theta_1 + \theta_2) \leq \frac{T_2}{\left(m_2 g \frac{L_2}{2} + F_L L_2 \right)} \quad (8)$$

From Equations (4) through (8), we can conclude that the first joint has a narrower safe working range than the second joint under the same joint torque threshold value because its numerator value will always be smaller than that of second joint. Similar analysis and conclusion can be obtained under the first joint angle range of $\pi/2 < \theta_1 < \pi$.

The static simulation model described above is implemented using MATLAB to evaluate the system under varying arm dimensions, masses, load size and joint angles. The model used in the static simulation has the dimensions $L_1=0.55\text{m}$, $L_2=0.64\text{m}$, $m_1=2.5\text{kg}$, $m_2=2.5\text{kg}$, $m_L=4\text{kg}$, i.e., the same as that used in dynamic simulation.

FINDINGS

The result from the static analysis agrees with the result from the dynamic analysis with a typical operating speed of 7.2 degree/sec, and the result is shown in Figure 4. This means that the static simulation model can be used, rather than the more complex dynamic simulation model, because of the slow operating speeds of UGVs. This finding leads to efficiencies at the simulation model development phase. However, static simulation is not always able to take the place of dynamic simulation because the joint torques increases as the robot operating speed increases due to inertial effects. Thus, it is important to determine the acceptable manipulator operating speed for which the static simulation can be used instead of the dynamic simulation.

Comparison Between Dynamic and Static Simulations

During the dynamic simulation, for each selected first joint angle, θ_1 , the second joint angle, θ_2 , is varied from 0 to 2π radian, i.e., one full revolution. This makes the manipulator move through a full range of motion and provides data for all operation states.

During the static simulation, the second joint angle is varied from 0 to 2π , i.e., one full revolution, with an increment of $\pi/100$ radian for each selected first joint angle. The joint torques are then calculated using the relations listed in the previous section.

A worst-case is when the absolute value of the first joint torque is at a maximum. When the joint torque thresholds of joint motors are known, the failure of the robot manipulator will occur when the joint torque exceeds the threshold joint torque. For example, assuming that the joint torque threshold is 50 Nm, the first joint of the manipulator used in the simulation will fail in various positions. Various manipulator orientations are evaluated using both dynamic and static simulations, and the results for the dynamic simulation with a typical operating speed of 7.2 degree/sec and the static simulation at the first joint angle of $\pi/6$ with threshold joint torque of ± 50 Nm are shown in Figure 4. Based on this result, we can conclude that the static simulation can be an alternative to the dynamic simulation. In the next section, we will evaluate the validity of the conclusion under the selected operating speeds.

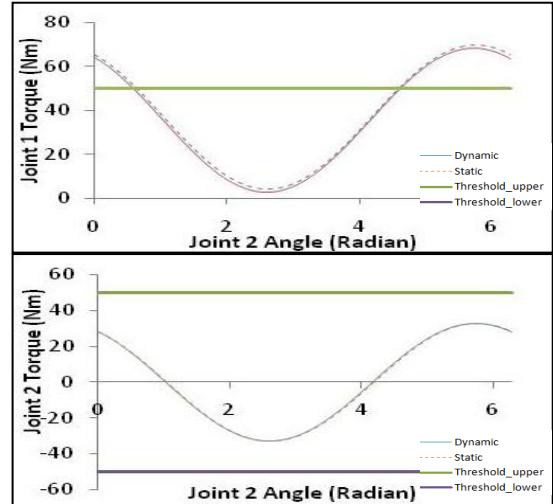


Figure 4: Static and dynamic simulation results are shown with threshold joint torque of 50 Nm for the first joint angle of $\pi/6$ radians with an operating speed of 7.2 degree/sec (i.e. full revolution in 50 sec)

Statistical Assessment of Operating Speed Using Static Simulation

A statistical assessment via an F-test is further conducted to determine an acceptable operating speed range for using the static simulation to approximate the dynamic simulation. The F-test is simply used to test for significant differences in the approximation errors between the high operating speed and the low operating speed when the static simulation is used to replace dynamic simulation. As given in Equation (9), the approximation error is evaluated by the mean of the sum of squares of errors (MS), which is calculated by the sum of squares of individual errors between the static analysis result and the dynamic analysis result and dividing it by the sample size minus 1. Since the operating speed of 1 degree/sec is considered very slow for robot arm operations, we assume that the dynamic analysis result with the speed of 1 degree/sec and static analysis result will be almost identical, and their differences is considered as the minimal approximation error. As shown in Equation (10), the denominator of F statistic (MS_B) is the MS of dynamic analysis under 1 degree/sec compared with the static analysis, while the numerator of F statistic (MS_A) is determined using the dynamic analysis under each given operating speed compared with the static analysis. F values for the operating speed of 1, 5, 7.2, 36, 72, 108, 144, and 180 degree/sec are calculated for various first joint orientations, and the values for the first joint angle of $\pi/6$ are shown in Table 2.

$$MS = \frac{\sum_1^N e^2}{N - 1} \tag{9}$$

$$F = \frac{MS_A}{MS_B} \tag{10}$$

Here, e denotes the difference between dynamic analysis result and static analysis result, and N denotes the sample size. In the paper, $N=201$ is used.

The tabulated critical F-value of 1.227 is found at the significance level of 5% with the degrees of freedom of 200 for both MS_A and MS_B . Therefore, based on the F-test, the proposed static simulation is acceptable under all the operating speeds up to 36degree/sec.

Operating Speed (degree/sec)	F value for the first joint	F value for the second joint
1	1.0	1.0
5	1.0	1.0
7.2	1.0	1.0
36	1.2	1.0
72	5.1	1.0
108	22.0	1.0
144	67.6	1.0
180	163.9	1.0

Table 2: The calculated F values for the operating speed of 1, 5, 7.2, 36, 72, 108, 144, and 180 degree/sec with the first joint angle of $\pi/6$ radians.

Identifying the Test Range for the Joint Torque Saturation Failures

The developed static simulation model is further applied to identify the test range under various joint torque threshold values for the joint torque saturation failures. Assuming the joint torque threshold values are 30Nm, 50Nm, and 70Nm, the failure region versus the safe operating range of the manipulator is shown in Figure 5. This plot will be very useful for acceptance testing planning because it shows the boundaries of operating range under different joint torque thresholds. For example, when the joint torque threshold of 50Nm is given, the circled line in Figure 5 form a failure boundary. Then the failure range can be excluded from acceptance testing immediately.

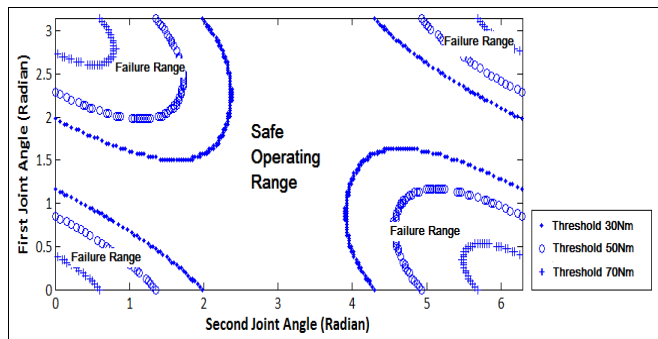


Figure 5: Failure range and safe operating range of the two-link planar robot arm for threshold values (30, 50, and 70Nm) are shown in terms of first and second joint angle.

Identifying the Test Range for the Rollover Failures

The static simulation model discussed in the previous section can be combined with rollover failure simulation. First, additional model parameters such as platform dimensions and weight are defined. Next, equations for static analysis are derived, and this static simulation model is implemented using MATLAB software. Several initial robot orientations can be chosen to test whether the system rolls over while the robot arm travel through its full range of motion, and those robot orientations are shown in Figure 6. All these orientations are evaluated, and the result for the right-tilt orientation is shown in Figure 7. As we can see from Figure 7, the initial robot orientation has a significant impact on failure and its safe operating range, and this result can provide guidance for operators to avoid rollover failures. Additional test methods can be based on these initial robot orientations, including a dragging capability test and degradation in lifting capability without flippers.

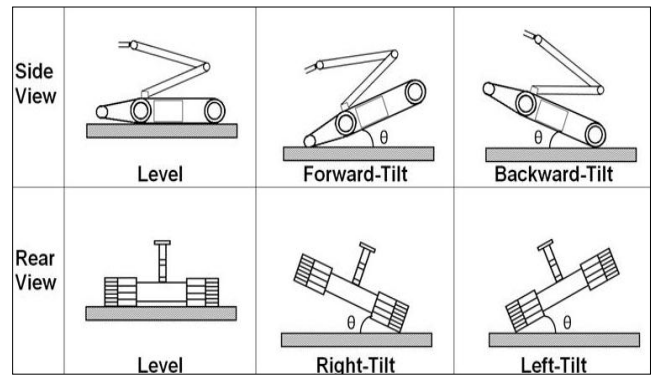


Figure 6: Example initial robot orientations for test set up. Test measures the safe operation range of the tilt angle for different robot arm orientations.

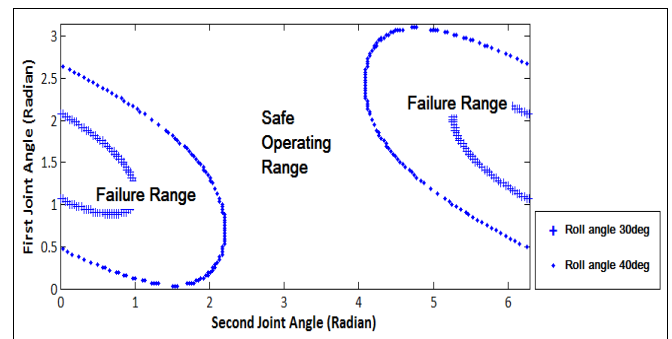


Figure 7: Failure range and safe operating range of the two-link planar robot arm for Right-tilt (roll) angle of 30 and 40degree are shown in terms of first and second joint angle.

SUMMARY AND CONCLUSIONS

Reliability of UGVs is still far below the military standard and user expectations although its application and usage is growing faster than ever before. Therefore, the importance of studying the reliability of UGVs and field robots is quite clear.

In this paper, we have introduced a simulation-based methodology to determine UGV acceptance test scenarios. We have studied failures due to joint torque saturation and rollover. The results showed that the static simulation model can be used, rather than the more complex dynamic simulation model, because of the slow operating speeds of UGVs. This finding leads to efficiencies during the simulation model development phase. Simulation based acceptance testing design can significantly reduce the time and cost, and this can provide a better understanding in UGV failure modes, which will help both designers and users to improve the reliability of UGV systems. In addition, once a comprehensive acceptance test is available, it can provide guidance to users regarding the purchase, deployment, and use of UGV systems in various environments.

FUTURE WORK

To achieve the goal of higher reliability in UGV operations, the simulation of various types of failure modes must be evaluated. Eventually, a comprehensive and complete UGV acceptance test needs to be developed.

In order to establish system reliability, randomness in environmental conditions and user operations must be included in the simulation to estimate the probability of failure accurately.

A preliminary set of user training materials is needed prior to starting a user acceptance test. Well-designed user training can significantly reduce human interaction failures in the field.

ACKNOWLEDGEMENT

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