



**GRRC Technical Report 2009-01**

# **Reliability and Failure in Unmanned Ground Vehicle (UGV)**

**Authors:** Phuoc-Nguyen Nguyen-Huu  
Joshua Titus  
**Advisors:** Prof. Dawn Tilbury  
Prof. Galip Ulsoy

**Date of completion: February 10, 2009**



## **ABSTRACT**

The main goal of this report is to review the literature on reliability of Unmanned Ground Vehicles (UGV) and to identify key research areas for improving their reliability. The report begins with definition of a UGV and explanation of the need for improving its reliability. The literature review, which summarizes two major UGV reliability studies, is followed by a classification of failures section. Common failure and reliability analysis methods are then discussed. The report concludes by a summary of key points and identification of research areas for improving UGV reliability.

## TABLE OF CONTENTS

I.	Introduction.....	5
1.1	What is a UGV? .....	5
1.2	Why there is a need to improve UGV reliability? .....	6
1.3	Purpose and scope of this report .....	6
II.	Literature review .....	7
2.1	Carson’s study.....	7
2.2	Reliability studies for UGVs used in museum.....	12
2.3	DARPA PreceptOR .....	13
2.4	ATRV-Jr .....	14
2.5	Acceptance Testing.....	15
2.6	Performance Simulation.....	17
III.	Classification of failure.....	19
3.1	Failure classification approaches .....	19
3.2	Failure types.....	20
IV.	Methods of failure and reliability analysis.....	21
4.1	Failure Modes and Effects Analysis (FMEA) .....	22
4.2	Fault Tree Analysis (FTA).....	23
4.3	Block Diagram .....	25
4.4	Markov analysis .....	26
4.5	Fishbone diagram.....	26
4.6	Comparison of the reliability and failure analysis techniques .....	28
V.	Summary and Conclusions .....	29
1.	Data collection and analysis.....	29
2.	Design for maintainability .....	30
3.	Self fault diagnosing and fault tolerance .....	30
	References.....	31
	APPENDIX A.....	33

## I. Introduction

### 1.1 *What is a UGV?*

In the broadest sense, an Unmanned Ground Vehicle (UGV) is any piece of mechanized equipment that moves across the surface of the ground and serves as a means for carrying or transporting something, but explicitly does not carry a human being [1]. In another definition [2], a UGV is a ground-based mechanical device that can sense and interact with its environment. UGVs, which are often used in military terminology, are actually ground-based mobile robots. UGVs could be classified further based upon their characteristics such as mode of locomotion, type of control system, and intended operating area. One possible UGV taxonomy based on mode of locomotion is wheels, tracks, legs, and articulated body [3].

UGV structures may vary from one to another, but in general a UGV consists of the following parts [4]:

**Sensors:** A ground robot needs to have sensor(s) in order to perceive its surrounding, and thus, permit controlled movement. Sensors' accuracy is extremely important for robots that operate in highly unpredictable environments such as the battle field or fires.

**Platform:** The platform provides locomotion, utility infrastructure and power for the robotic system. The configuration has a strong influence on the level of autonomy and interaction a system will have in an unstructured environment; highly configurable and mobile platforms are typically the best for unstructured terrain.

**Control:** The level of autonomy and intelligence of the robot depends largely on its control systems, which range from classic algorithmic control to more sophisticated methods such as hierarchical learning, adaptive control, neural networks and multiple robot collaboration.

**Human machine interface:** The human machine interface depends on how the robot is controlled. The interface could be a joystick and a monitor control panel in the case of teleoperation, or more desired advanced ones such as speech commands from the commander.

**Communication:** Communication is essential in the case of military robots, where both accuracy and secrecy of information exchange are crucial. The communication happens between humans and robots and possibly between robots. Most current and planned ground robots involve a human in the decision making cycle while the robot is in operation. This requires a communication link between the human and the vehicle. The communication method varies from radio link to fiber optics.

**System integration:** The choice of system level architecture, configuration, sensors and components provide significant synergy within a robotic system. Well-designed robotic systems will become self reliant, adaptable and fault tolerant, thereby increasing the level of autonomy.

## 1.2 Why there is a need to improve UGV reliability

UGVs have many potential applications and the demand for them is ever increasing. Application of UGVs ranges from military missions such as reconnaissance, surveillance and combat; industrial and home usage in, for instance, harvesting crops and cleaning floors; to special tasks such as rescue operations. UGVs, therefore, have drawn interest from many researchers and organizations, especially the military, since 1960s [1]. As a result, UGVs have been deployed in military operations with increasing numbers over the years [5].



Figure 1: A view on development of UGV [5]

In fact, UGVs were used for inspection at checkpoints in Iraq and Afghanistan [6], and for rescue operations during the World Trade Center disaster [7].

However, despite having gained some success, UGVs appear far from being reliable. Reliability studies of UGVs [8][9] show that the Mean Time Between Failure (MTBF) for a UGV is currently only between 6 to 24 hours. Reports on applications [6][7] also showed that the UGVs' reliability were low. Therefore, there is a need to improve UGV reliability.

## 1.3 Purpose and scope of this report

The purpose of this report is to review the literature on reliability of UGVs and to identify key research areas for improving their reliability. Although there are other types of UGVs, this study covers only ones with wheels and tracks.

## II. Literature review

The literature review shows that there are a number of studies on UGV reliability. The most notable studies are conducted at the Center for Robot-Assisted Search and Rescue (CRASAR), University of South Florida by Carson and Murphy [2][8][9][10]; studies conducted by Nourbakhsh [11] and Tomatis [12] on UGVs used in museums; the DARPA PreceptOR studies by Krotkov, Kelly and Jackel [13][28][31]; the ATRV-Jr case study by Ioannou et al. [29]; the acceptance testing methods discussed by Kramer and Murphy [30]; and the performance simulations done by Perkins, N., Akcabay, D., Ma, Z.. This section summarizes the major findings of the studies.

### 2.1 Carson's study

The work at CRASAR is presented in 4 papers [10][8][9] (in chronological order) and one thesis [2]. The later papers include the data presented in the previous ones and also additional data. The thesis encompasses all of the data and sums up the works presented in the papers.

#### *Data sources*

Overall, the study includes data from 13 studies and 15 different models in Urban Search and Rescue or military field applications. Two studies explore failures encountered in a limited amount of time in a real crisis (World Trade Center rescue response). Four studies cover regular use of thirteen robots over two years at CRASAR. The remaining eight studies are field tests of robots performed by the Test and Evaluation Coordination Office at Fort Leonard Wood. Total of 28 UGVs are considered in this study. The UGV sizes range from man-packable one to a 60-ton M1 tank that was converted to teleoperation for experimental purposes [9].

Among those studies, only the CRASAR study gathers key information that is sufficient for a quantitative reliability analysis. More than 2100 hours, over 500 of which is field work, of robot operation have been recorded, in the CRASAR study. The data was recorded with information on failure, repair and frequency. The WTC data was recorded in different ways from the CRASAR study, and also did not provide sufficient data for a complete quantitative analysis. Data from Tesco is available mostly in qualitative form. Raw data was not available for analysis [2].

#### *Taxonomy of failures*

The failures are classified according the source of failures, which are divided into human and physical ones. Physical failures are classified further into effector, sensor, control system, power, and communications, while human failures are classified into design and interaction. Under interaction, there are two sub-categories: mistake and slips. The terminologies are explained in the following [8] and figure 2, pg 8.

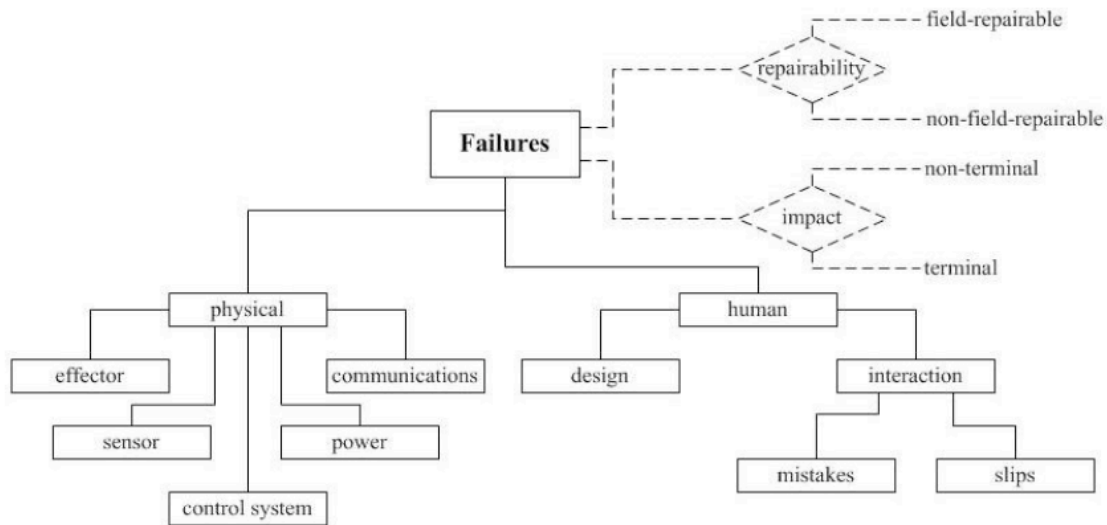


Figure 2. The taxonomy of mobile robot failures. Classes are shown with solid lines, and attributes with dashed lines. [8]

**Control system** A robot subsystem that includes the onboard computer, manufacturer provided software, and any remote operator control units (OCU).

**Effector** Any device that performs actuation and any connections related to those components.

**Mistakes** Human failures caused by fallacies in conscious processing.

**Slips** Human failures caused by fallacies in unconscious processing.

#### *Summary of the reliability data*

The data was not gathered using the same approaches, therefore, it cannot be presented in a synthesized way. For this reason, data will be in both tabulated form and representative examples.

#### Mean Time Between Failure and availability:

Only data for CRASAR study is available here, which is summarized in the following table, pg 9.



Table 1. Summary of results from CRASAR Reliability [8]

Manu.	Type	% of Usage	MTBF(hrs)	Availability	Ave. Downtime(hrs)
Inuktun	Field	94%	6.14	90%	177
iRobot	Field	28%	6.27	36%	207
Nomad	Research	100%	19.50	94%	61
Inuktun	Field	80%	10.27	27%	39.65
iRobot	Field	24%	4.57	88%	0.66
Nomad	Research	94%	149.08	99%	0.3

Note: % of Usage is the percentage of total time that the robot was used in fields.

Over 3 years, CRASAR conducted 2 studies: the original study for the first two years, and the follow-up study for the third year. Totally 2100 hours, which includes 500 hours of field work, has been covered [8]. The data for the original study is presented on the top half of the table, and the bottom half is for the follow-up study.

#### Relative frequency of physical classes

Table 2. Probability by Physical Class from the CRASAR Studies Results from the original study above with the follow-up study's results below [8].

Manufacturer	Effector	Control System	Power	Comms	Sensing
Inuktun	0.50	0.34	0.03	0.00	0.13
iRobot	0.58	0.17	0.25	0.00	0.00
Overall	0.50	0.33	0.09	0.00	0.09
Inuktun	0.45	0.32	0.00	0.02	0.12
iRobot	0.22	0.30	0.15	0.22	0.11
Overall	0.36	0.31	0.06	0.10	0.12

Table 2 shows that effectors are the most common source of physical failures, followed by the control system, sensors, communications, and power. However the results are very different for the PANTHER.

Table 3. Probability by Physical Class for M1 PANTHER [8]

Model	Effector	Control System	Power	Comms	Sensing
PANTHER	0.11	0.54	0.09	0.00	0.26

Table 3 shows the primary problem for the PANTHER is the control system, followed by sensing, while effector problems are encountered much less often. Only power has a similar probability of causing failures across the three studies. The reason for the big

difference in probability of effector failures in two cases is probably that PANTHER uses the M1 platform which has proven its reliability over 20 years.

### ***Effector***

This is the most common type of failure across the 11 studies which explored physical failures. Common failure sources in the original CRASAR study were shear pin and pinion gear in the geometry shifting mechanism, thrown tracks, track slippage. A common cause of those failures was dirt and other small debris that entered the moving devices and caused wear, slippage and blockage.

Results from the reliability studies [8][10] show that tracked vehicles were more prone to effector failure than wheeled platforms. In the original reliability study 96% of the effector failures occurred on tracked rather than wheeled vehicles. 57% of the effector failures were the tracks working off their wheels (known as de-tracking), usually due to excessive friction at the ground surface.

### ***Control System***

The control system failure class includes any problems caused by the on-board computer, manufacturer provided software, and Operator Control Units (OCUs). This is the most common failures in TECO's M1 PANTHER II study (54%), and the second most common field failures in the CRASAR reliability studies. None were reported in the WTC Engineering study.

An example for control system failures is that the robot was simply unresponsive (60% of field control system failure). Since the problem is solved by rebooting the robot, it was assumed to be a control system problem. Control system problems were also found in M1 PANTHER II. The problems' symptoms ranged from sluggishness to a complete loss of steering, sometimes manifesting in only one direction at a time. There were some cases erratic and unstable behavior occurred. Acceleration sometimes was uncontrolled, i.e. the RPMs were shooting up to a critical level for no apparent reason.

### ***Communications***

Dropped signals in wireless controlled robots was the most frequently encountered problems in communication. The WTC study reported one incident where the robot lost communication in under 20 feet, instead of its usual mile or more. The structural steel of the WTC was thought to have a significant impact on the range of communication.

The communication problems also include video drop-out in experiments with the PANTHER. This was because the teleoperation equipment could not transmit video through interposed materials or foliage. Video bandwidth and reliability limitations even impacted the performance of operators in line-of-sight scenarios.

## ***Sensor***

The sensor category covers failed sensors and problems with their connections. These failures tend to be less common than effector and control system failures, with only 9% of the failures analyzed in the original reliability study and 11% of failures in TECO's M1 PANTHER II study. At the WTC sensors were more of a problem. Due to incorrect lighting and occluded camera views, an average of 24% of search time was lost each time the robot was used to search a void. By far the most common failed sensor in all of the studies was the camera. It was also the only sensor common to all of the robots' sensor suites.

The WTC Engineering study identified two categories of intermittent sensor failures: occluded camera and incorrect lighting. Occluded camera was defined as a state in which the entire camera view is blocked by obstacles. This failure was found to occur during 18%, on average, of the total time the robots spent searching a void. Note that this percentage is high despite the fact that 100% obstruction was required. The incorrect lighting category included states in which the lights were completely off (in which case the operator could not see) or were in transition between intensities. This failure was less common, occurring 6%, on average, of the total time the robots spent searching. Lighting problems were also mentioned in TECO's ARTS study. The camera's automatic iris did not adjust enough for the operator to see to maneuver the robot.

TECO's M1 PANTHER II study cited sensor problems which do not tend to occur under lab conditions. Bumpy terrain, sudden changes in lighting, and rainy weather caused problems for the on-board cameras. Since human operators rely heavily on camera views while teleoperating a robot, these minor failures made it difficult to control the robot from the remote operator control unit (OCU). The PANTHER study also mentions cases where camera lenses were covered in moisture, dirt, or mud.

## ***Power***

Based on the results from the CRASAR studies and TECO's M1 PANTHER II study, power failures do not cause many of the failures that occur in the field. The WTC Engineering study revealed no failures due to batteries and their related connections during the two week rescue response. This was probably due to the fact that the robots were not used for an extended period of time. The longest period of time a robot was continuously used was a little over 24 minutes, therefore the batteries were not heavily taxed. Power may be more reliable than the other systems since it is the least affected by environmental hazards.

In the reliability studies half of the power failures on the robots are due to the battery and its connections. The PANTHER platform suffered repeatedly from low batteries and low fuel. TECO had recurring failures during the DEUCE study (DEUCE, Deployable Universal Combat Earthmover, is a 35000lb earthmoving machine produced by

Caterpillar that was used in the TECO study). One of the two DEUCE platforms suffered from clogged fuel filters, requiring a replacement roughly every six hours.

## 2.2 Reliability studies for UGVs used in museum

There are two studies on UGVs used in a museum. The first one was conducted at the Carnegie Museum of Natural History, where Sage, an autonomous UGV was being employed as a full-time staff [11]. The reliability data is summarized in the following table.

Table 4: Sage's performance [11]

Sage performance resulted for the period 05/22/98–02/03/99

Total number of days in the period (save renovation)	174
Total number of totally error-free days	135
Total number of errors	41
Total number of days Sage was down all day	7
Total number of hours Sage is operational	4,008 h
Total number of hours Sage is in motion, giving tours	999
Uptime, last 30 days	97.5%
Mean time between failure, hours	97 (4 days)
MTBF, most recent 50 days (3/18/99–5/7/99)	400 (16.6 days)
Mean time to repair, hours	1
Average linear distance traveled by Sage per error-free day	1.3 km
Approximate distance covered by Sage for the period	226
Total number of collisions (obstacle avoidance failures)	0
Total number of navigation failures	0

The recorded failures, apart from ones that are due to humans, include software programming errors and stereotypical robotic errors: insufficient agility of the obstacle avoidance module; relay board communication difficulties; failure of the wall plug and the break-beam wheel position sensor; motor controller failures and one operating system crash. In the second study, N. Tomatis et al [12] have developed RoboX, an autonomous robot aimed a tour guide application. The robot achieved a MTBF of 20.9h. More data is summarized in the following table.

Table 5: RoboX's performance [12]

Run time	2447 h
Movement time	1750 h
Travelled distance	582.9 km
Average speed	0.09 m/s
Failures	117
MTBF	20.9 h
Visitors	124031

### 2.3 DARPA PreceptOR

The Defense Advanced Research Projects Agency (DARPA) Perception for Off-road Robotics (PreceptOR) is a project to implement a rigorous evaluative test program to quantitatively evaluate UGVs on such factors as autonomy level, waypoint acquisition, failure rate, speed, and communications bandwidth. This process has led to new approaches in planning, perception, localization, and control which will result in greater overall reliability [28]. The main focus of this study was to improve vehicle perception, resulting in better overall performance and the ability to perform more advanced tasks, thus improving UGV utility.

The PreceptOR project developed a control architecture as shown in [28]. Three nested layers of autonomy are shown. Higher levels use more abstract, lower resolution, spatially expansive models, while incorporating more memory, longer prediction horizons, and consequently slower response times. The reactive autonomy layer performs operations requiring fast reaction times while the perceptive autonomy layer utilizes moderate amounts of memory for prediction and path planning operations. The top-level deliberate autonomy layer utilized large amounts of memory to create environmental models for strategic vehicle guidance. This architecture creates a real-time planning navigation system with many benefits.

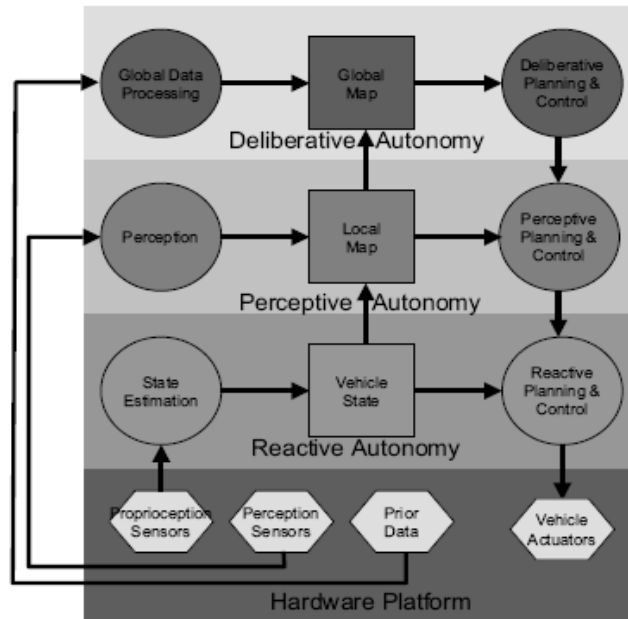


Figure 3: Software Architecture

Testing done during this project showed that a human-driven UGV was 5 times faster than a teleoperated UGV and 10 times faster than an autonomous UGV [13]. This indicates the need for substantial improvement, especially in autonomous UGV operation. Since this test was conducted, autonomous operation has improved as shown in the Learning Applied to Ground Vehicles (LAGR) study [31]. The teams working on this project (8 teams total) passed the first phase with 1.2 to 2.2 times faster travel speed through the courses. The second phase requires 3 times faster travel speed and was ongoing at the time of this study. This is a substantial

improvement (more than 2 times improvement in 36 months) considering that it took 10 years for performance to double in the past [31].

With improved UGV perception, there are also improvements in many other areas of performance as shown. This is because perception of the environment is essential for reliable operation of UGVs in the field. A fully functioning UGV with poor perception of its environment has very limited usefulness (especially for autonomous operation); although it can perform all the physical tasks required, if the UGV never makes it to the destination then the entire mission is a failure regardless of the functionality of the UGV.

## 2.4 ATRV-Jr

A very in-depth study was conducted on the ATRV-Jr UGV platform with emphasis on power and its effect on the endurance of the vehicle. The requirements and tasks a UGV must perform are increasing every day, and with that the power requirements are increasing as well. UGVs must not only carry more payload, but also more sensors, faster processors for better control and numerous actuators all while maintaining good range, long operating lifetime and the ability to cover almost any terrain.

This study found that the main power draw was from the electric motors, sensors, cooling devices and control systems as shown in [29] for the original sensors and processors.

Table 6: ATRV-JR Original Sensors [29]

Processor Type	Power Demand (Watts)	
	Idle State	Max Work Load
Intel Pentium D 820	50	134.3
Intel Pentium 4	49	130.6
Intel Pentium M	20.8 at 1.2GHz	30 at 2.66GHz
Intel Pentium 0.13 $\mu$ m	30 at 1.6GHz	76 at 3.2GHz
Intel Pentium 90nm	30 at 1.866GHz	88 at 3.33GHz
AMD Athlon64, +3500	11.6	45.6

Using a combination of low power sensors and energy efficient processors the power consumption was reduced by 45%. This results in a total runtime increase from 1.1 hours to 2.5 hours, an increase of about 230%.

Table 7: ATRV-Jr Low Power Sensors [29]

Sensor Type	Power (W)
Sony CCTV Camera – FCB (2)	3.6
GPS-Carmin 18, 12 channel	0.3
IMU – ETB	0.5
Range Finder – SICK LMS-200-30106	17.5
<b>Total Consumption</b>	<b>21.9</b>

Table 8: ATRV-Jr Processor Power Consumption [29]

Sensor Type	Voltage (V)	Power (W)
Laser	24	17.5
Fans (two)	24	4.08
IMU	12	3
Fan	12	0.24
Sony Cameras (two)	12	60
GPS	9	0.6
Compass	5.1	0.1
<b>Total Consumption</b>		<b>85.52</b>

Further improvements in the efficiency of sensors and the electric drive motors could increase operating time even more. The study also found that it was more efficient to decrease power consumption by increasing efficiency then to add more power capacity and thus more weight. Power consumption and its optimization will play an important part in improving UGV reliability in the field.

## 2.5 Acceptance Testing

Creating standardized acceptance testing is vital towards improving UGV reliability in the field. Almost no work has been published to date on UGV acceptance testing, therefore, this study [30] aims to not only document a set of standardized test procedures but also to optimize the tests performed to catch as many reliability issues as possible before the UGV is used in the field.

The test methods used were automated and forced the UGV to repeatedly exercise all aspects and combinations of components on the UGV for 6 hours. This process uncovered many failures common with those that occur in the field, showing that testing by the user can predict failures. The process also demonstrated that testing by the manufacturer can provide important design data that can be used to identify, diagnose, and prevent long-term problems. Also, the structured testing environment showed that sensor systems can be used to predict errors and changes in performance, as well as uncovering un-modeled behavior in subsystems [30].

During testing, the failures shown below in the table were observed [30]. The main failure modes observed were Control Failure (A), Power Failure (B), and Communications Failure (C).

Table 9: Shows the types and numbers of failures suffered by both robots [30]

Robot	Control Failure (A)	Effector Failure	Power Failure (B)	Communications Failure (C)	Sensing Failure
Robot 1	2	0	1	2	0
Robot 2	2	0	1	0	0
<b>Total</b>	<b>4</b>	<b>0</b>	<b>2</b>	<b>2</b>	<b>0</b>

### ***Control Failure***

This failure was the most common in the tests conducted, as shown by the 4 instances above. Upon closer examination of the failures, we can see that some of the control failures could be prevented. There were signs of instability before the robot flipped over, as shown in the figure [30].

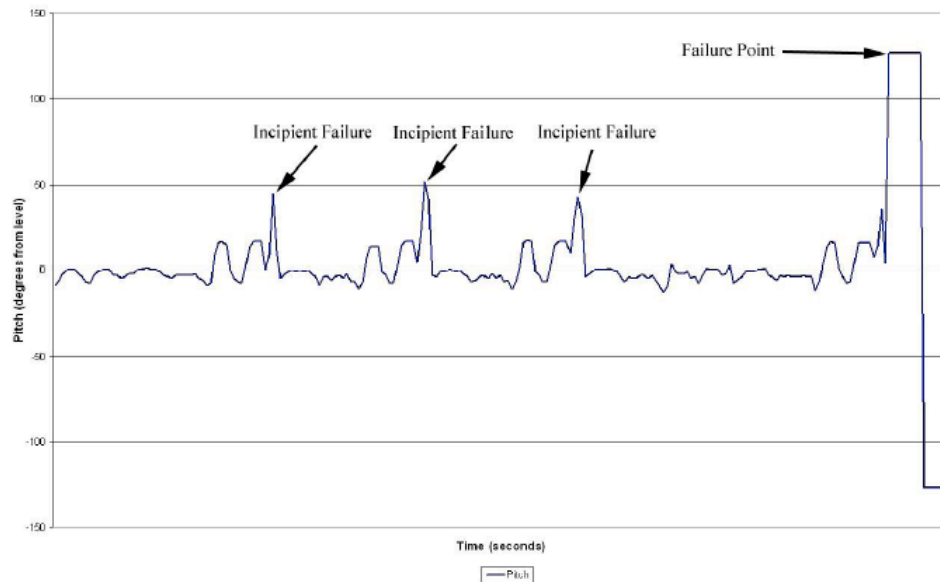


Figure 4: Plot of pitch over time for robot 1 showing a failure presaged by fluctuations in pitch angle that warn of impending failure [30]

Acknowledging the warning signs and taking preventative action through the system control could prevent many of the control failures seen during these tests (2 of the 4).

### ***Power Failure***

When power fails it leaves the UGV completely incapacitated. The ability to predict when this failure mode may occur is therefore a very useful attribute. The figure, pg 17 [30] shows the fluctuations in current to the right track motor, where the regions of low power events are highlighted. These events preceded the actual power failure, so if current is measured we could predict failure before it caused an actual failure in the field, increasing the overall reliability of the UGV.



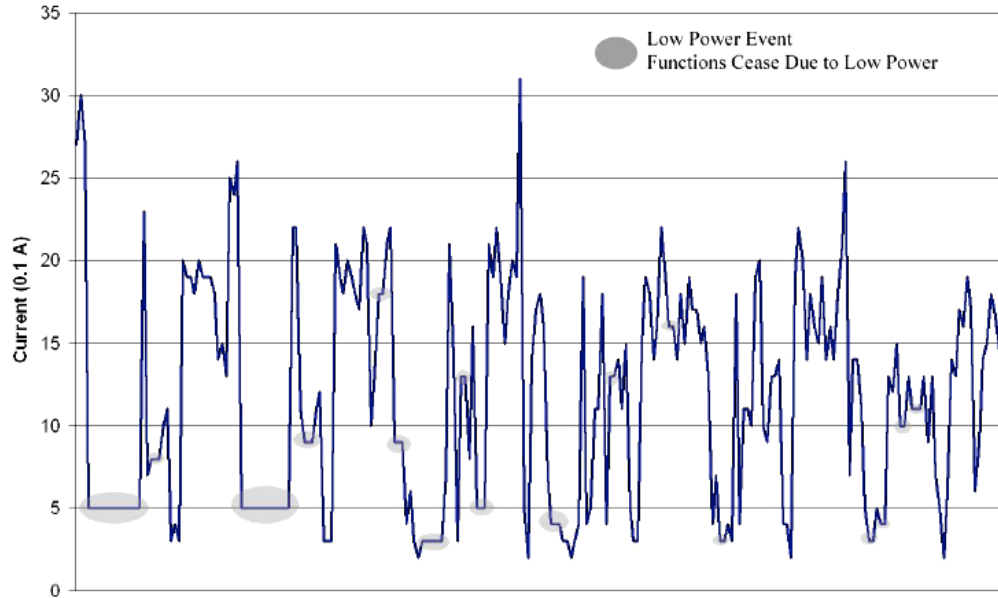


Figure 5: Plot of right track current over time for Robot 2 showing low power events [30]

### ***Communications Failure***

Without communications a UGV is likely lost, especially with the limited autonomous capabilities of UGVs today and the likelihood that they will be operated in environments which are dangerous for UGV retrieval. The failures observed in these tests were mainly due to poor design of the tether, but similar failures can occur for a number of reasons and therefore communications should be thoroughly tested for robustness before UGV deployment in the field.

### ***Conclusions***

The important aspects of acceptance testing are that it is continuous (so that failures occur rapidly if they occur at all), that it involves the full range of motion, performance and capabilities of the UGV to test as many failure modes as possible, and that it be structured and repeatable for testing UGVs on a large scale. It was shown that a combination of manufacturer quality testing and end user verification testing would be ideal for catching the most common failure modes in UGVs. Prevention of failures in the future could also be further improved by regular interval testing.

## **2.6 Performance Simulation**

Numerous studies have been done on the dynamic limitations of UGVs used today, and how these limitations affect performance and reliability in the field. One study [32] evaluated UGV performance on inclines and stairs, with a focus on urban maneuverability. Vehicle performance on other terrains such as soil or grass is covered more extensively in [33]. The major conditions found to have the greatest effect on

performance were traction (including tread penetration if applicable), center of mass, track velocity and area of contact (contact region). These four areas are investigated in detail; with one of the most interesting results being that the best climbing performance on an incline was achieved with the center of mass 21.6% to the rear of the vehicle [32].

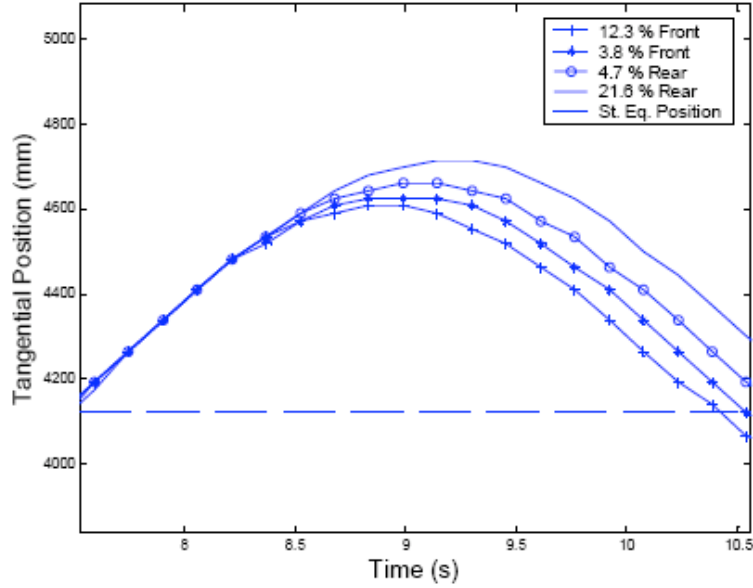


Figure 6: Effect of mass center position on height reached on incline (tangential position)

Another interesting finding was that while track speed influenced the peak tangential position it did not affect the mean position reached substantially. So, increasing the track speed of a UGV will help if it reaches the top of the incline before slipping, otherwise the track speed will not influence the resulting mean position substantially as shown in [32].

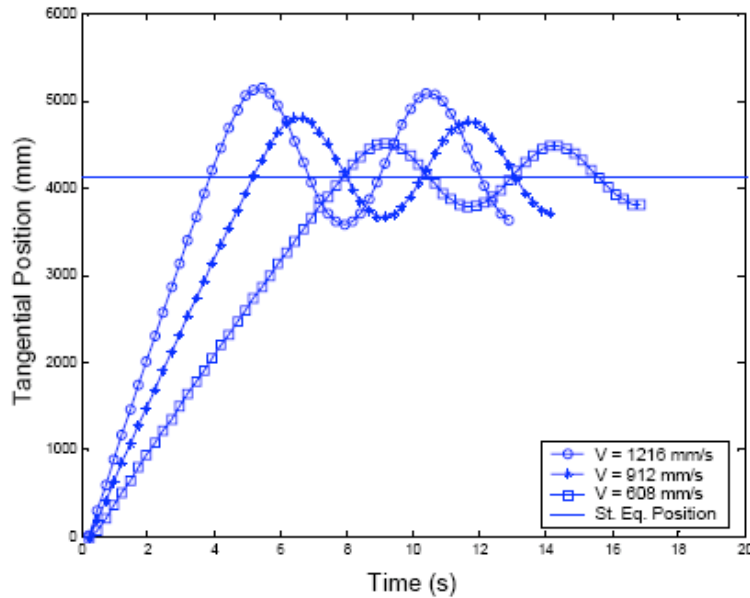


Figure 7: Effect of track speed on height reached on incline (tangential position)

An interesting performance increase was found by varying the contact region. With the use of only partial contact (in the rear) with slightly greater rear bias center of mass (38.6% rear) a greater tangential position was reached. This puts the vehicle in an unstable position, however, and must be carefully controlled to avoid rollover.

It is important to fully understand the dynamic limitations of each UGV so that these limits are not exceeded during operation in the field, thus increasing their operational reliability. If these limits are exceeded, it is very likely that the UGV will be incapacitated and that the mission will be a failure, regardless of whether or not an actual component failed. This is a particularly serious failure mode, especially in situations where it is dangerous for human extraction, which is the case in many of the situations in which UGVs are used today. For these reasons, we need to keep dynamic performance limitations in mind when we are working on improving vehicle reliability.

### **III. Classification of failure**

#### **3.1 *Failure classification approaches***

Carson classifies failures according to where the failures happen. While this approach offers a good overview on distribution of failure, it does not indicate the root causes. In order to identify the areas for reliability improvement, however, it is necessary to know the root causes of failures. Therefore, failures are classified according to their root causes in this study. The following fishbone diagram, figure 8 pg 20, shows the classification. Please take note that the classification does not present an exhaustive list of lower level causes.

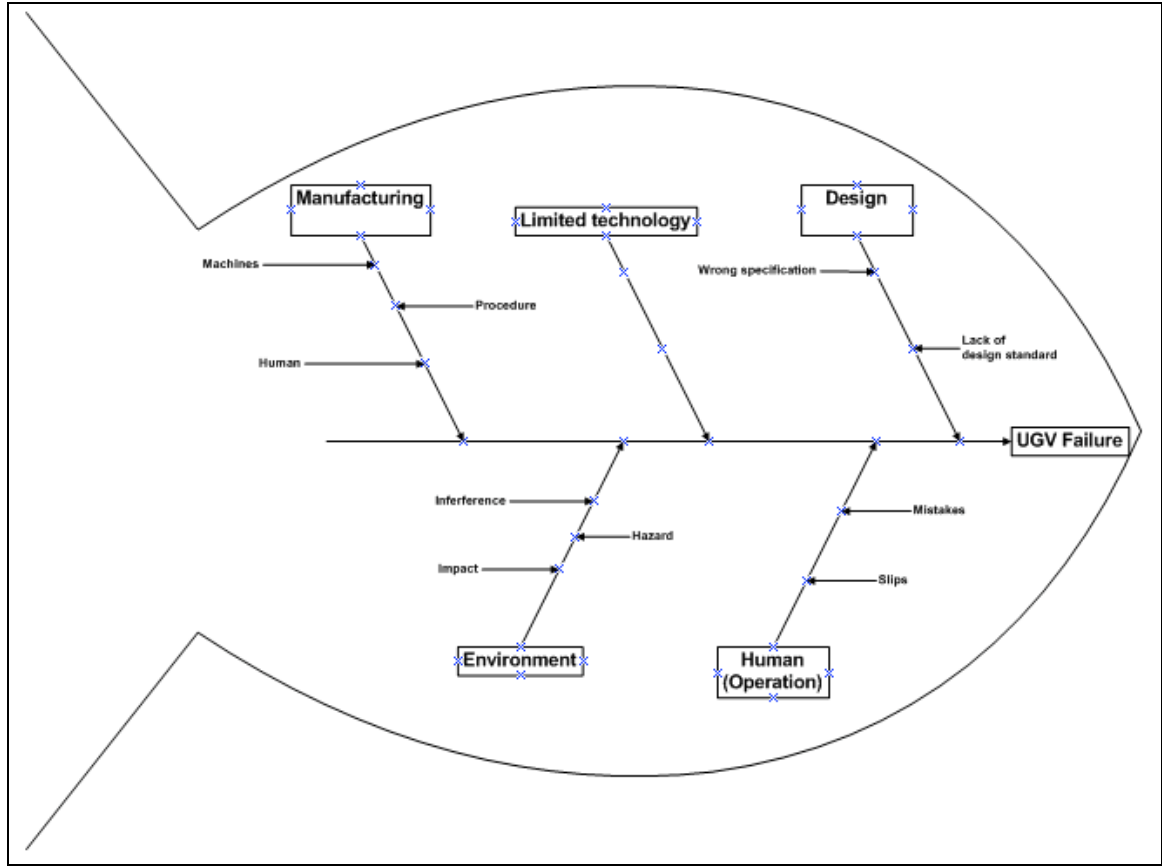


Figure 8. Failure classification according to root cause

### 3.2 Failure types

**Design:** This type of failure is caused by improper design that does not enable UGVs to operate reliably. Flaws in design often result from inadequate evaluation of the operating environment. The UGVs designed in this case lack necessary specifications to operate in the specific environment. This type of failure was encountered in all Carson's studies. TECO studies reported an incident that the platform was not designed to traverse mud, sand and water. Consequently, the open gearing for the drive motors and articulating arms collected debris causing the platform to grind to a halt. In the WTC study, one UGV's track was softened until that it became loose and fell off because the temperature in the void that the robot was exploring exceeded 122 degrees Fahrenheit. Excessive heat was also the reason for some wheel warping incidents in CRASAR studies. The root causes of all the failures above are design flaws since they could be avoided by improving the designs.

**Limited technology:** There is a class of failure of UGV that is unavoidable, or at least not yet avoidable, in certain operating conditions. That is the type of failure caused by limitations of current technology in achieving a desired task. One such technology is the environment perception technology. In the United States Defense Advanced Research Projects Agency (DARPA) evaluation experiments [13], in which several autonomous

UGVs were evaluated in different terrains, the UGVs appeared to be operating well in some terrains but encountered failures in other. In fact, the UGVs found difficulties in recognizing or differentiating objects such as a fallen log, tree with diameters larger or smaller than 5 cm, and tall grass. Further more, no system was able to handle slopes reliably. This proved that no matter how reliable the UGVs were, the perception technology limitation would not allow the UGVs to operate reliably in some conditions.

**Manufacturing:** Failures in this case are caused by manufacturing defects, which may be the result of improprieties in machines, procedures, and human operations. The defects may cause component failures, and, consequently, lead to lower reliability of the UGV. Although not many manufacturing failures were reported in the Carson's studies, the UGVs were not used for a long time and, thus, such failures were not frequently seen. One example of this type of failure is that there were new robots which arrived with several wires pinched by the cover plates [10].

**Environment:** Failure in UGVs also may be caused by the environment. The major environmental causes of failure are interference of small objects such as dust or small rocks; and presence of hazardous agents such as excessive heat and rain. Many failures in Carson's studies fall into this type. For example, a rock stuck in the track of the PANTHER in TECO study, or the track became softened and loose because of excessive heat. However, environmental causes, in many cases, cannot stand as sole causes of failure. They often go with design and/or manufacturing causes to make a failure happen. In the above example, if the track was designed to withstand temperatures of more than 122 degrees Fahrenheit, then failure would not have occurred even if the environmental cause, i.e. a temperature of 122 degrees Fahrenheit, existed.

**Operation:** Improper (human) operation may cause failures in UGVs as well. This type of failure is caused by operators and can be classified further into two categories: mistake and slips. These two sub-categories were proposed by Carson and Murphy [8] and defined as follows. Mistakes are human failures caused by fallacies in conscious processing, while slips are human failures caused by fallacies in unconscious processing. In studies covered by Carson's work, there were more operation failures in WTC study than in others. This is understandable since operators in the WTC study would had been in a more stressful situation than in other studies. One example of mistake is that the operator drove the robot into an area, in the WTC site, where the incline was too steep for it, because he could not judge the height of the hole.

#### **IV. Methods of failure and reliability analysis**

This section presents what are the common methods in failure and reliability analysis and when to use them. The following methods are chosen because they are the most commonly used, and seen to be suitable for UGVs.

#### **4.1 Failure Modes and Effects Analysis (FMEA)**

Failure Modes and Effects Analysis (FMEA) is the most widely used analysis procedure in practice at the initial stages of system development. Often, development of an FMEA is a mandatory requirement in the aerospace and automobile industry. In their desire to receive a quality product, some customers mandate a proof that the vendors have considered modes in which the product could experience a failure in use and have undertaken measures to prevent or mitigate those potential failures [14]. The purpose of FMEA is to identify the different failures and modes of failure that can occur at the component, subsystem and system levels and to evaluate the consequences of these failures. It involves an analysis of the system to determine the effect of component or subsystem failure (1) on the overall performance of the system and (2) on the ability to meet the performance requirements or objectives. The FMEA is usually performed during the conceptual and initial design phases [15].

In general terms, FMEA is used to do the following [16]:

- Ensure that all conceivable failure modes and their effects are understood.
- Assist in the identification of system weaknesses.
- Provide a basis for selecting alternatives during each stage of operation.
- Provide a basis for recommending test programs and improvements.
- Provide a basis for corrective action priorities.

The analysis is performed by a multidisciplinary team of professionals participating in the product design. Reliability predictions, analysis and even modeling (for functional failure modes, dependent failure modes, conditional failure modes, and so forth) are necessary and important inputs to a good FMEA. Reliability modeling is often done using Reliability Block Diagrams or Fault Tree Analysis, the latter is also often used as a method to combine the failure mode analysis with the reliability modeling [14]. FMEA is conducted in a tabular form. The following table is a typical FMEA form.

Table 10. A sample form of FMEA analysis [17]

Product: Component Name: Component Number: Revision Number: Effect on Purchasing: Yes/No						Developer: Dates: Report Number: Sheet of Sheets: Revision Number: Last Updated:				
Product, Device, Process or system name & number	Function	Possible Failure Mode	Effect of Failure	Cause of failure	Control Procedure	O	S	D	R	Remarks/ Action taken

**O: Occurrence of failure**, measured on the scale:  $1 = 10^{-6}$ ,  $2 \& 3 = 10^{-5}$ ,  $4 \& 5 = 10^{-4}$ ,  $6 \& 7 = 10^{-3}$ ,  $8 = 10^{-2}$ ,  $9 = 10^{-1}$ ,  $10 = 10^0 = 100\%$  chance of occurrence

**S: Severity of failure**, measured on the scale: 1= unlikely to be detected, 2= 20%, 3 = 40%, 4 = 60%, 5 = 80%, 6 = 100% chance of a customer return, 7 = Failure results in a customer complaint, 8 = Failure results in a serious customer complaint, 9 = Failure results in non-compliance with safety standard, 10= Failure results in death.

**D: Detection of failure**, measured on the scale: 1= Failure will be detected, 2=80%, 3=70%, 4=60%, 5=50%, 6=40%, 6=40%, 7=30%, 9=10% chance of detection, 10=no chance of detection

**R: Risk Priority Number (RPN)** = Occurrence rating x Severity rating x Detection rating. Base on the RPN score, actions are recommended to eliminate failure effect, or reduce failure effect or accept failure effect.

## 4.2 Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a logic diagram that displays the relationship between a potential event affecting system performance and the reason or underlying causes for this event. The reason maybe failures (primary or secondary) of one component of the system, environmental conditions, human errors, and other factors [18]. Conducting an FTA offers the following values:

- Directing the analysis to ferret out failures
- Pointing out the aspects of the system important to the failure of interest
- Providing a graphical aid by giving visibility to those systems management who are removed from design changes

- Providing options for qualitative and quantitative systems reliability analysis
- Allowing the analyst to concentrate on one particular system failure at a time
- Providing an insight into system behavior

A fault tree analysis involves the following steps [18]:

1. Definition of the TOP event
2. Construction of the fault tree
3. Qualitative and, if desired, quantitative analysis of the fault tree

One example of FTA is shown in the following diagram.

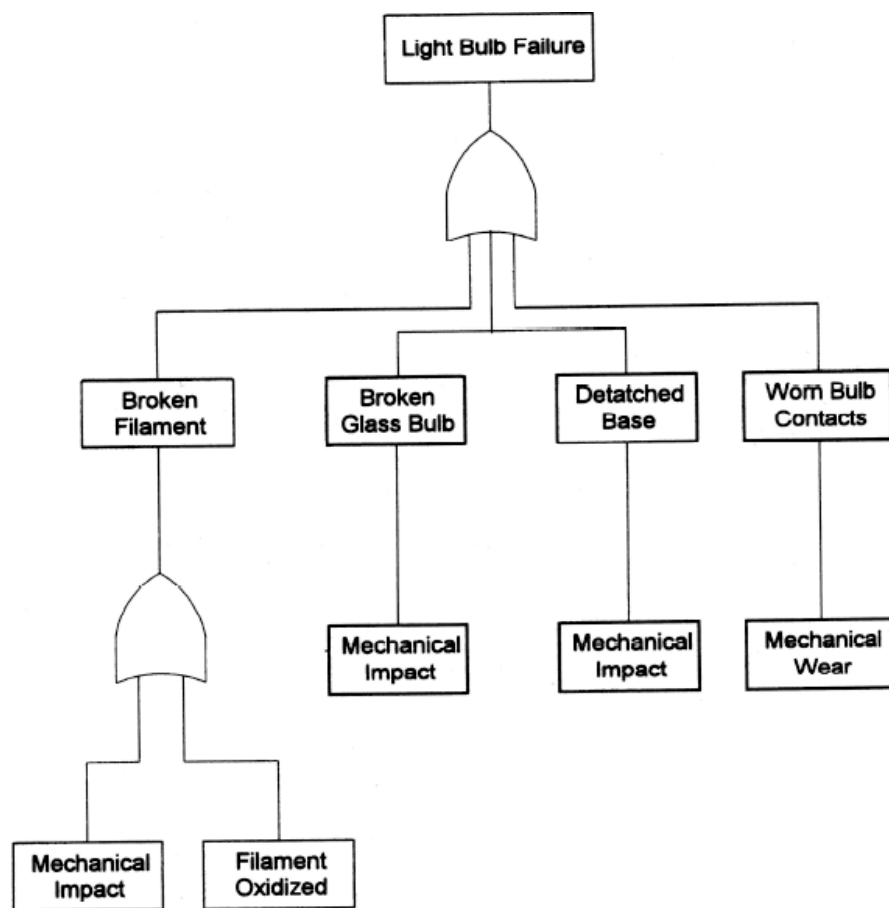


Figure 9: An example of FTA method [18]

For an explanation on the logical symbols, please refer to the Appendix A



It is important to understand that a fault tree is not a model of all possible system failures or all possible causes for system failure. A fault tree is tailored to its top event that corresponds to some particular system failure mode, and the fault tree thus includes only those faults that contribute to this top event. Moreover, these faults are not exhaustive as they cover only the faults that are assessed to be realistic by the analyst. [19]

### 4.3 Block Diagram

Block diagrams (also called a reliability network) are one of the simple and effective methods which enables the system failure probability to be evaluated in terms of the component performance characteristics. The first step in the reliability prediction is to identify failure modes of the system and collect reliability information on all of its components. A block with assigned probability of success or failure rate represents each component. Blocks are then connected together so as to form a reliability network which represents the reliability dependencies between components of the system [16].

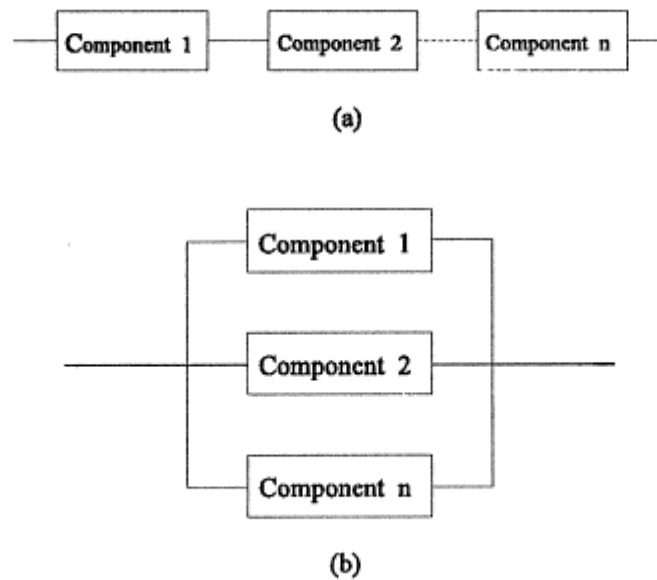


Figure 10: Reliability block diagrams: (a) Series configuration, (b) Parallel configuration [16].

A block with assigned probability of success or failure rate represents each component. Blocks are then connected together so as to form a reliability network which represents the reliability dependencies between components of the system.

#### **4.4 Markov analysis**

The Markov analysis approach has been frequently used for availability analysis using exponential distributions for failure times and repair times [15]. It is a powerful method which can handle a wide range of system behaviors. The method is particularly useful in representing situations where component failures are not independent [16]. This is an advantage compared to above methods such as FTA, in which the failures have to be independent. The Markov method is developed on the following assumptions [15]:

- At any given time the system is either in the operating state or in the failed state
- The state of the system changes as time progresses
- The transition of the system from one state to the other takes place instantaneously.
- The failure and repair rates are constant.

Due to the complexity of the mathematics involved, the Markov analysis is not presented in detail here. For an aid in understanding the use of Markov analysis, the result of it in a single-component system is the popular formula

$$Availability = \frac{MTBF}{MTBF + MTBR}$$

#### **4.5 Fishbone diagram**

Cause-and-effect analysis, also known as fishbone analysis, is a graphical approach to failure analysis [20]. It assists users in categorizing the many potential causes of problems or issues in an orderly way and in identifying root causes.

The cause-and-effect analysis is usually used when there is need to [21]:

- Study a problem/issue to determine the root cause
- Study all the possible reasons why a process is beginning to have difficulties, problems, or breakdowns
- Identify areas for data collection
- Study why a process is not performing properly or producing the desired results

A typical fishbone diagram is constructed by following the below steps [21]:

1. Draw the fishbone diagram.
2. List the problem/issue to be studied in the "head of the fish".
3. Label each "bone" of the "fish". The major categories typically utilized are:
  - The 4 M's: Methods, Machines, Materials, Manpower
  - The 4 P's: Place, Procedure, People, Policies
  - The 4 S's: Surroundings, Suppliers, Systems, Skills

4. Use an idea-generating technique (e.g., brainstorming) to identify the factors within each category that may be affecting the problem/issue and/or effect being studied. The team should ask... "What are the machine issues affecting/causing..."
5. Repeat this procedure with each factor under the category to produce sub-factors. Continue asking, "Why is this happening?" and put additional segments each factor and subsequently under each sub-factor.
6. Continue until you no longer get useful information as you ask, "Why is that happening?"
7. Analyze the results of the fishbone after team members agree that an adequate amount of detail has been provided under each major category. Do this by looking for those items that appear in more than one category. These become the 'most likely causes'.
8. For those items identified as the "most likely causes", the team should reach consensus on listing those items in priority order with the first item being the most probable cause.

#### 4.6 Comparison of reliability and failure analysis techniques

Method	What	When
FMEA	<p>A bottom-up approach used to identify the different failures and modes of failure and to evaluate the consequences of these failures. Three types:</p> <ul style="list-style-type: none"> <li>• Design: Potential failure related to design</li> <li>• Process: Potential failure related to processes those used to make a component, sub system, etc.</li> <li>• System: Potential failure related to sub system/ system interaction.</li> </ul>	Conceptual and Initial design phases
FTA	A top-down graphical approach used to express the probabilistic relationships among the various events that lead to the failure of the system.	<ul style="list-style-type: none"> <li>• Design and development stages [26], and after FMEA [15]</li> <li>• Identifying problems in existing products/services. [27]</li> </ul>
Fishbone Analysis	A graphical approach to assist users in categorizing the many potential causes of problems or issues in an orderly way, and in identifying root causes.	<ul style="list-style-type: none"> <li>• To analyze and find the root cause of a complicated problem</li> <li>• When there are many possible causes for a problem</li> <li>• If the traditional way of approaching the problem (trial and error, trying all possible causes, and so on) is very time consuming</li> <li>• The problem is very complicated and the project team cannot identify the root cause [9-4]</li> </ul>
Block diagram	A method to evaluate the system failure probability in terms of the component performance characteristics. It represents system structure.	Failure probabilities of all components are known.
Markov	An analysis to evaluate the availability analysis using exponential distributions for failure times and repair times	Useful in representing situations where component failures are not independent

## **V. Summary and Conclusions**

UGVs have many potential applications and the demand for them is ever increasing. UGVs have drawn interest from many researchers and organizations, especially in the military, since the 1960s. In fact, UGVs have been used in some military operations such as inspection at checkpoints at Iraq and Afghanistan, and rescue operation during the WTC disaster.

However, our literature review shows that UGVs, despite having gained some success, appear far from being reliable. Studies have shown UGVs' MTBF between 6 to 24 hours. Failures of UGVs operating in fields are various but can be classified, according to their root causes, into design, manufacturing, limited technology, environment, and operation failures.

To analyze UGV failure and reliability, common methods are Failure Modes and Effects Analysis, Fault Tree Analysis, Block Diagram, Markov Analysis, and Fishbone Diagram.

In order to achieve significant usage of UGVs, their reliability needs to be improved. From our study, the following research areas are identified as potentially important areas for improving UGV reliability.

### *1. Data collection and analysis*

Data on UGV failures is important for various reasons. First of all, information on how failures occur can be used in manufacturing and design processes to improve the reliability of UGVs. Secondly, research areas to improve UGV reliability, such as fault diagnosis and fault tolerance, require the knowledge of type and frequency of failure. Moreover, understanding UGV failure in the field is important to applying research results from indoor mobile robots to UGVs in fields. The importance of UGV failure data automatically leads to the need for suitable data collection and analysis.

However, our literature review shows that no systematic data collection and analysis methods have not been applied to UGVs. The UGV reliability related data found in the literature were presented in different ways, such as qualitative descriptions and tabulating data, without showing full aspects of the failures. Carson [2] classifies failures into categories but her work lacks significant quantitative data analysis and shows some inconsistencies in the results. The two primary reasons are limited data and lack of consistency in data collection methods. Therefore, there is a need for more widely acceptable data collection and analysis methods.

## *2. Design for maintainability*

The current UGV reliability is clearly low. There are some UGVs that have exceptionally high reliability such as the Mars Rover, but the reliability comes at very high financial cost. Furthermore, we do not expect a sudden shift in UGV reliability since the reliability improvement process takes time and the demand for UGVs, i.e. from military or industry, is still far from making UGV mass production possible, with the exception of those used in simple applications such as floor cleaning. Therefore, design for maintainability is important, at least in the near future, to counter the problematic fact that UGVs will fail.

One idea in design for maintainability is that we could use cheaper and lower-reliability robots to complete tasks by providing spare components or even spare robots. The lower-reliability robots are used and will be repaired or replaced if some failures occur. The concept of using spare components has been implemented successfully in many applications such as cars, electricity generators, but it is considered new in UGVs. Stancliff et al. [22], in 2006, proposed a method for mission reliability estimation for multirobot team design. The authors tried to find a balance between numbers of spare components and spare robots to complete the mission reliably while achieving low cost. But it seems that there has been no realization in hardware yet.

However, with UGVs' (desired) inherent characteristics, mobile and autonomous, and their (sometimes) extreme operating environments, such as battle fields, high temperature, and low-oxygen sites, UGVs present big challenges in achieving their maintainability. How do people perform UGV maintenance jobs in environments where UGVs are designed to be a replacement? If a human (doesn't do the maintenance jobs), then how does a UGV maintain jobs? One of the answers to these questions could be self-maintainability of UGVs. The UGV, firstly, must have the ability to communicate with the operators, or other UGVs to decide what is the solution for its failure, if not making the decision itself. Secondly, the UGV must be able to implement the solution itself. It could possibly reconfigure to a configuration that does not require the failed component(s). The other possibility is that the failed UGV communicates with a backup UGV to replace it.

## *3. Self diagnosis of faults and fault tolerance*

In order to achieve the objective of operating autonomously in environments where direct human intervention is not feasible, self diagnosis of faults and fault tolerance are the characteristics that UGVs must have. With these characteristics, UGVs are expected to be able to, firstly, identify faults by analyzing system data from sensors, and secondly, forecast the propagation of faults in the system, and lastly, propose actions to eliminate or mitigate the effect of the faults.

There has been significant research done in these areas [2][23][24][25]. However, there is evidence that most of the research works were done without investigating how UGVs fail in field [2][25]. Therefore, there is a need for incorporating the existing research work with the knowledge of UGVs' behavior in fields. In fact, there have been some successful testing of the theoretical work in a single mobile robot [23] or in multirobot teams [24][25]. The testing, however, was on indoor wheeled robots and with limited types of failure. To benefit from the existing research results in fault diagnosis and tolerance, collaboration with other research groups could be a key point.

## References

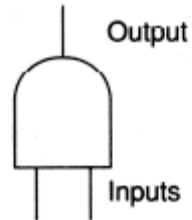
- [1] Douglas W. Gage, "A brief history of Unmanned Ground Vehicle (UGV) development efforts", *Special Issue on Unmanned Ground Vehicles, Unmanned Systems Magazine*, 1995.
- [2] Jennifer Carlson, "Analysis of How Mobile Robots Fail in the Field", *Master thesis, Department of Computer Science and Engineering, University of South Florida*, 2004.
- [3] Hirose S., "Three basic types of locomotion in mobile robots", *Fifth International Conference on Advanced Robotics. Robots in Unstructured Environments*, Pisa Italy, 1991.
- [4] Khursid J., Bing-rong H., "Military robot-a glimpse from today and tomorrow", *8<sup>th</sup> International Conference on Control, Automation, Robotics and Vision*, Kunming, China, 2004.
- [5] Purdy M. E., Presentation slide "Ground robotics technology", *Joint Ground Robotics Enterprise*, Department of Defense, June 2007.
- [6] B. Smuda et al, "Deploying of Omni-directional Inspection System in Iraq and Afghanistan", *US Army TARDEC*, 2004.
- [7] Mark Micire, "Analysis of the robotic-assisted search and rescue response to the World Trade Center disaster.", *Master thesis, Department of Computer Science and Engineering*, University of South Florida, 2002.
- [8] J. Carlson, R. Murphy, A. Nelson, "Follow-up Analysis of Mobile Robot Failures", *IEEE International Conference on Robotics and Automation (ICRA)*, 2004
- [9] J. Carlson, R. Murphy, "How UGVs Physically Fail in the Field", *IEEE Transactions on Robotics*, Vol. 21, N0 3, June 2005
- [10] J. Carlson, R. Murphy, A. Nelson, "Reliability Analysis of Mobile Robot Failures", *IEEE International Conference on Robotics and Automation (ICRA)*, 2003
- [11] I. R. Nourbakhsh et al, "An Affective Mobile Robot Educator with a Full-time Job", *Artificial Intelligence*, ELSEVIER, 1998.
- [12] N. Tomatis et al, "Building a Fully Autonomous Tour Guide Robot: Where Academic Research Meets Industry", *Proc. Int. Symp. On Robotics*, Stockholm, Sweden, 2002.
- [13] Krotkov et al, "The DARPA PerceptOR evaluation experiments", *Autonomous Robots*, 2006.
- [14] Milena Krasich, "Can Failure Modes and Effects Analysis Assure a Reliable Product?", *Reliability and Maintainability symposium*, 2007

- [15] S.S. Rao, "Reliability-based design", McGraw-Hill, 1992.
- [16] B .S.Dhillon and A . R . M . Fashandi, "Safety and reliability assessment techniques in robotics", *Robotica* (1997) volume 15 , pp 701 – 708 , Cambridge, 1997.
- [17] Geoff Vorley, Quality management presentation,  
[http://www.fmeainfocentre.com/presentations/fmea\\_presentation.pdf](http://www.fmeainfocentre.com/presentations/fmea_presentation.pdf) , Accessed in Feb 27<sup>th</sup> 2008.
- [18] W. R. Blischke, "Reliability: Modeling, Prediction, and optimization", John Willey & Sons, Inc., 2000.
- [19] NASA, "Fault Tree Handbook with aerospace application", 2002.
- [20] R. K. Mobley, "Root cause failure analysis", Newnes, 1999.
- [21] Fishbone diagram a problem-analysis tool  
<http://www.isixsigma.com/offsite.asp?A=Fr&Url=http://quality.enr.state.nc.us/tools/fishbone.htm>, accessed in Feb 27<sup>th</sup> 2008.
- [22] S. B. Stancliff, J. M. Dolan, A. Trebi-Ollennu, "Mission Reliability Estimation for Repairable Robot Teams", *Advanced Robotics System*, 2006.
- [23] P. Goel, G. Dedeoglu, S. I. Roumeliotis, G. S. Sukhatme, "*Fault Detection and Identification in a Mobile Robot Using Multiple Model Estimation and Neural Network*", Proceedings of the 2000 IEEE International Conference on Robotics & Automation, 2000.
- [24] L. E. Parker, "*ALLIANCE: An Architecture for Fault Tolerant Multirobot Cooperation*", IEEE Transactions On Robotics And Automation, 2001 .
- [25] L. E. Parker , B. Kannan, "*Adaptive Causal Models for Fault Diagnosis and Recovery in Multi-Robot Teams*", Proc. of IEEE International Conference on Intelligent Robots and Systems, 2006.
- [26] B.S Dhillon, "*Design reliability: Fundamentals and applications*", CRC press, 1999.
- [27] Concordia University, Fault Tree Analysis,  
<http://web2.concordia.ca/Quality/tools/15fta.pdf> accessed in March 7, 2008.
- [28] Kelly, A. et al., "*Toward Reliable Off Road Autonomous Vehicles Operating in Challenging Environments*", The International Journal of Robotics Research, Vol. 25, No. 5-6, 449-483 (2006) DOI: 10.1177/0278364906065543
- [29] Ioannou, S.; Dalamagkidis, K.; Valavanis, K.P.; Stefanakos, E.K.; Wiley, P.H. "*On improving endurance of unmanned ground vehicles: The ATRV-Jr case study*", 14th Mediterranean Conference on Control and Automation, MED'06 [0-9786720-0-3] Ioannou yr:2006
- [30] Jeffrey A. Kramer and Robin R. Murphy, "*UGV Acceptance Testing*", Proceedings of SPIE - The International Society for Optical Engineering, v 6230 I, Unmanned Systems Technology VIII, 2006, p 62300P
- [31] Jackel, L.D.; Hackett, D.; Krotkov, E.; Perschbacher, M.; Pippine, J.; Sullivan, C., "*Locomotion and navigation*", Communications of the ACM, v 50, n 11, Nov. 2007, 55-9
- [32] Perkins, N., Akcabay, D., Ma, Z., "*Predicting the Mobility of Tracked Robotic Vehicles*", Proceedings of IMECE04, 2004 ASME International Mechanical Engineering Congress November 13-19, 2004, Anaheim, California USA
- [33] Wong J.Y., 2001, "*Theory of Ground Vehicles*", 3rd Edition, Interscience

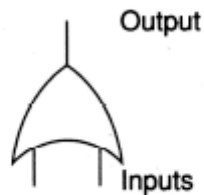


## APPENDIX A

### Importan symbols used in FTA



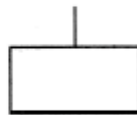
**AND gate**  
The output event is generated only if all the input events are present simultaneously.



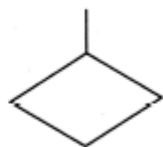
**OR gate**  
The output event is generated if any one or more of the input events are present.



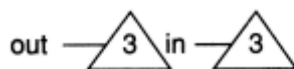
**Basic failure**  
A basic fault or event caused by a component or sub-assembly for which a probability can be assigned (from known empirical data).



**Intermediate event**  
A fault or event caused by a combination of other events via a logic gate.



**Undeveloped event**  
A fault that is not subdivided into basic events due to lack of information or importance. The event must be expanded or developed later.



**Transfer events**  
An entire part of the tree is transferred to other locations of the tree.



**Basic event**  
A basic event that is a normal occurrence while the system is operating.