Abstract—Mobile Robots have large application areas such as search and rescue, transportation of material, surveys and exploration. Dynamic stability during mobile robot exploration plays a key role in the success of any mission. Real world environments such as uneven or rough terrain can be potentially hazardous to such missions. An Inertial Measurement Unit (IMU) can be used to obtain state information of the robot during exploration. In this paper, the use of a 6-Degree of Freedom IMU to assist in maintaining dynamic stability during mobile robot exploration is discussed. A simulation involving the use of an IMU during searching is conducted and the results are presented. Results show that readings from the IMU can be used to detect slip and tilt and corrective measures can be used to prevent the robot from falling in uneven terrain.

Index Terms: Inertial Measurement Unit, Dynamic Stability, Mobile Robots

I. INTRODUCTION

Mobile robots are increasingly being used in autonomous exploration. Search and rescue in disaster sites and exploration in uneven terrain such as planetary exploration are not conducive for human exploration and also present considerable hazards in the form of uneven terrain, slippery surfaces and slopes. For a mobile robot to successfully navigate this terrain, it is required to cope with these hazards. State information of the robot during the exploration provides valuable information, which can be used by the robot to adapt itself to the terrain. Although the use of Global Positioning Systems, odometers and magnetic compasses are used to provide position information, none of them actually provide real time information about the robot such as slippage and tilt. A six-degree of freedom (DOF) inertial measurement unit consisting of accelerometers and gyroscopes can be used to provide information regarding the robot's current attitude, and accelerations experienced by it, which can then be used to implement feedback control on the robot to adapt itself to the uneven terrain.

Autonomous ground mobile robots have several application areas such as reconnaissance, patrol, search and rescue, planetary exploration and military applications. To accomplish tasks on rough terrain, control methods must consider the characteristics of the vehicle and of its environment. Failure to understand these, could lead to vehicle endangerment and mission failure [1]. The use of a tracker that combines rate gyros and accelerometers with a compass and tilt orientation sensor and a GPS system to determine the 2-D components of velocity, position (trajectory) and heading has been discussed [2]. Inertial navigation systems have been widely used in aerospace applications but are only now being seriously exploited in robotics applications where they have considerable potential. Methods of extracting information about robot position and orientation have been derived theoretically [3]. Ongoing research to achieve dynamic stability focuses on modifying the kinematic configurations of a robot to achieve the desired goal. In [4], a discussion on how changes in the vehicle's internal configuration can be used to adjust the center of gravity to guarantee a stable motion is presented. Analyses of the acceptable positions for the center of gravity given the slope's inclination, and the friction between the vehicle and the surface have been performed [4]. A modification of the kinematic configuration of the robot as a means of coping with uneven terrain has also been discussed in [5].

An IMU consists of accelerometers and gyroscopes, which measure the acceleration, and rate of rotation respectively. The use of a six axis Inertial Measurement Unit along with a stereovision system in order to provide attitude, height and velocity information for an autonomous helicopter is discussed in [6]. Accelerometers are sensitive to uneven terrain because any disturbance from a perfectly horizontal position will cause the sensor to detect a component of the gravitational acceleration g. However, additional information about the tilt can be provided to the accelerometer to cancel the gravity component projecting on each axis of the accelerometer [7]. The geometric configuration of a robot equipped with an Inertial Navigation System has been discussed, and error models for the sensors have been generated [3]. Linear position estimation with the accelerometer has been performed but no evidence to suggest that the information
is sufficient to maintain dynamic stability is presented. A prototype of an Inertial Navigation System for use in mobile land vehicles such as robots has been discussed but no reference to dynamic stability is made [8]. The use of three-axis gyros and accelerometers, essential for position estimation and for heading estimation during driving and stair climbing has been described in [9]. The dead reckoned method, used to turn corners on landing works well only if the dimensions of the landing is known.

The sections are organized as follows. A section on the Inertial Measurement Unit and its calibration is followed by a brief analysis of dynamic stability of robots on slopes. Finally, two scenarios to the test the effectiveness of the IMU in assisting dynamic stability of a robot, performing a structured search, are described and the simulation results are presented.

II. THE INERTIAL MEASUREMENT UNIT & CALIBRATION

An Inertial Measurement Unit is a device used to detect and measure attitude and motion. It uses its inherent inertial mass to detect the current acceleration and rate of change in attitude. Small changes in the external force acting on the IMU cause the embedded accelerometer and gyroscope of the IMU, to measure changes in acceleration and angular rate due to the applied force. The IMU contains a computational unit to perform the position calculations from the sensor readings. A six-degree of freedom Inertial Measurement Unit manufactured by Rotomotion, which uses the RS232 Serial Interface, was used to assist in maintaining stability during mobile robot exploration.

A disadvantage with using the IMU is that errors accumulate over time as acceleration needs to be double integrated to get position. It is therefore important to calibrate the measured signal to evaluate the performance of the IMU. Usually, the IMU forms one component of the navigation system and together, with the use of a GPS, can prove to be highly useful in Mobile Robot Exploration.

Calibration parameters were obtained and then used to determine an accurate model of the real sensor, called a sensor model, which was introduced into a simulation of the robot performing a search in uneven terrain. This explained in Section IV. The sensor model influenced the readings in terms of corrupting them with noise depending on the accuracy of the Inertial Measurement Unit. These readings were then used to implement control algorithms for stability during exploration in the simulation.

During the experiment to calibrate the IMU, a tool kit consisting of a robotic arm was interfaced with LabView, which is software that can measure the angle $\theta$ of the robotic arm. The arm was treated as a pendulum since it was constrained to have 2 degrees of freedom. Coordinate frames were assigned to the IMU (Fig 1), which was attached to the end of the robotic arm. The robotic arm was then raised to an angle and released. It swung in a pendulum like motion thereby exciting the Inertial Measurement Unit (Fig 2). Different orientations of the IMU attached to the robotic arm ensured that all the components (in the X, Y and Z directions) were excited. 3 data sets for each of the different orientations were collected and used for calibration.

At any time, gravity acceleration influences are superimposed to the sensor outputs of sensors, which are not perpendicular to the gravity vector [10]. Since the orientation of the sensor is known at any time of the measurement and the readings are affected by a constant acceleration due to gravity (9.81 m/s$^2$), a gravity term depending on the angle had to be added on to the linear acceleration (Fig 3).

Given the measured acceleration and the theoretical value of acceleration, parameters that map the measured value onto the theoretical value were calculated. These parameters determined the sensor model that was used in the simulation described in Section IV. The Least mean squares algorithm was used to find the coefficients that relate to producing the least mean squares of the error signal which is the difference between the desired and the actual signal. The calibration obtained was a gain and offset and did not model sensor noise (Fig 4).

The IMU measures the change in angle over time. The angular velocity was computed from the angle of the robot arm, by differentiating it with respect to time. The data from the IMU was then calibrated using the method of least squares as before to obtain parameters gain and offset. The results of the calibration are shown (Fig 5).
Dynamic Stability during mobile robot exploration is dependent on the center of gravity (COG) of the robot and the line of action (LOA). The LOA acts vertically downward from the center of mass of the object along the gravity vector. During locomotion, if the line of action is further from the points of contact of the wheels with the ground, the robot will topple. From the design of the robot, an estimate of the maximum slope $\theta$ it can climb can be computed by analyzing the static stability of the robot. When $\theta$ increases beyond a certain angle, the line of action is outside the point of contact of the wheels causing the robot to topple (Fig 6). The IMU readings were monitored to ensure that this condition never occurred so that the robot would not climb a slope, greater than the threshold value determined. However, this is not sufficient to achieve dynamic stability as several factors such as velocity, acceleration, slip and other factors affect the robot. A simple case to illustrate that the IMU cannot be used as a stand alone unit for dynamic stability is shown in Fig 7 where a robot moves from a relatively flat surface, heading towards a slope. At the point after it has taken off, there exists a clockwise moment $M_1$ given as $M_g \cdot d_1$. If the robots current velocity is not very high, and the degree of the slope is small, it will land as shown in Case 1 meaning that it will generate an anti clockwise moment $M_3$ which is given as $M_g \cdot d_3$. If $M_3$ exists, the robot will not topple and continue to move down the slope. However, if the robot is moving with a high velocity or the degree of the slope is high (or both), a clockwise moment $M_2$ given as $M_g \cdot d_2$ is generated on landing which will cause the robot to topple over as shown in Case 2. In both the cases, the IMU will record large values of acceleration, or tilt of the robot. However, since the robot is traveling with a high velocity and encounters an unforeseen object such as a rock or a bump, no corrective action can be taken as the readings from the Inertial Measurement Unit cannot be used to implement any control on the robot after the event has already occurred.

The readings only provide a means for implementing control such as preventing the robot from climbing a steep slope, slipping across smooth surfaces or stopping and taking preventive measures when the IMU readings predict that the robot is unstable.
exerted on an object can be controlled.

A search algorithm in which the mobile robot has to traverse the 3D environment in straight lines and sweep the entire area was designed. The robot was designed to have six wheels and uses a differential steering so that it can turn around on the spot, which can be extremely helpful in uneven terrain. In order to perform a structured search (Fig 8), besides navigating, it is important for the robot to have exact knowledge of its current location. It is assumed that the robot is equipped with a GPS and is given prior information about the area it needs to explore, such as the dimensions of the area. From these, the robot calculates the required path for the structured search. A proportional differential controller was used to control the velocities of the wheels of the robot, and ensure that the robot followed the ideal search path established from the prior GPS information.

Once a method for the structured search was established and the IMU calibration was completed, a sensor model of the IMU (described in Section II) was introduced into the simulation. The IMU was assumed to be located at the center of gravity of the robot. Any force experienced by the robot would now be acting on the IMU, thereby enabling measurement of accelerations and angular rate experienced by the IMU. This would give us an estimate of the accelerations and angular rates experienced by the robot. It was decided to model the terrain based on contour maps of a region in order to be able to analyze the success and failure cases. Nastran performs finite element analysis on friction between the wheels and point of contact on the ground, and as a result, slip occurred in uneven terrain depending on the slope of the surface. The readings from the IMU were analyzed in each of the failure cases, and were used to control the robot.

A. Scenario 1: In the first case, terrain was modeled to test how an IMU could be used to measure the accelerations in a direction perpendicular to the motion of the robot; thereby providing sufficient information to indicate that the robot was slipping sideways. A contour map of the terrain is shown (Fig 9). A graph of the position of the robot (Fig 10) demonstrates that the robot continues to slip due to the slope although the controller tries to ensure that the desired Y position (indicated by the dashed lines in Fig 10) and desired angle are achieved. The path followed by the robot is completely wayward and the robot has incurred a huge drift from its ideal path. The information obtained from the IMU is now used to help the robot in maintaining stability if it slips while navigating slopes. The readings from the IMU indicated variations and increased Y accelerations (Fig 11) as the robot moved across the slope.
time interval where it experiences large variations in Y Acceleration due to the slip between $t = 6$ and $t = 8$ seconds (Fig 12). A Graph of the position of the robot as it moves across the slope is shown in Fig 13.

The graph shows the robot turning and climbing the slope, back towards the ideal path to be followed during the search (Compare Fig 10 and Fig 13 at time = 14.84s). Thus the IMU readings can be useful in detecting slip and triggering necessary counter measures. It is however noted that the robot misses an area of the search (indicated by the circle around the ideal path in Fig 13) due to the fact that it slips, and the terrain cannot be accessed while the robot tries to climb back up the slope. It may be required that the robot drives around and finds an alternate path to cover the area that has been missed out.

**B. Scenario 2:**
In this case, the robot was driven up a ramp, such that one side of the robot went up the ramp while the other remained on a flat surface. This caused the robot to tilt about its X-axis enabling us to obtain information from the IMU about the Roll. The robot was initially driven up the ramp to see how it performed without any knowledge of its current orientation. A brief illustration is shown in Fig 14. The robot begins to tilt to its left while climbing the ramp and eventually flips over when the line of action from its center of gravity acts outside the point of contact of the wheel and the ground. A graph of the readings from the IMU which is a measure of the Angular Velocity of the robot indicates a large variation in the angular velocity at a time just after $t = 7$ seconds (See Fig 16). The Orientation of the robot was obtained by integrating the angular velocity. The information about the orientation of the robot and its angular velocity were used to control the robot. If the robot goes over a small bump at a reasonable speed, it can experience a high angular velocity. Hence this information alone is not sufficient to implement control on the robot. The orientation of the robot combined with information about the roll, pitch or yaw can be used to implement control. If the measured orientation was greater than the chosen threshold and the robot experienced a high angular velocity (greater than the threshold chosen), the path followed by the robot was altered so that it drove around the slope it was trying to climb (Fig 15). The threshold angle was chosen based on the design of the robot and the dynamic analysis performed in Section III. The turn is triggered due to the measured increase in angular velocity detected by the IMU.
If the orientation of the robot about its X-axis became greater than 20 degrees and it experienced an angular velocity greater than 30 deg/s, it was made to turn in the direction in which it tilted. Since the robot tilts to its left as it climbs the ramp, it indicates the presence of a slope to its left. When the measured roll exceeded the threshold, the robot turned left to face the slope, went down the slope (in this case, get off the ramp) and around the ramp. As before, if the measured roll was high, the robot turns to face the slope and climbs down a little instead of continuing to climb at a tilted orientation and later drives around the steep slope. The measured angular velocity between t = 6 and t = 8 seconds is shown in Fig 16. Just after t = 7 seconds, the angular velocity exceeds 30 deg/s. Graphs of the X - Orientation of the robot at around the same time show the robot making a sharp turn to its left (Fig 17). The final path of the robot using the IMU for control is shown in Fig 18. In the case of increased readings in the pitch, simple control such as reversing down the steep slope, or slowing down if it is too steep to proceed further downward were used.

When the robot hits a bump or encounters a pit while traveling at a relatively high speed, the IMU will measure an increased acceleration and/or change in angular velocity. However, this information is not sufficient to initiate corrective measures as the dynamic stability of the robot may already be affected depending on the degree of the bump or pit. The information from the IMU can be used to evaluate the nature of the terrain and learning algorithms can be used to plan an ideal path across this terrain. e.g. for a dormant volcano exploring robot, the crater might prove to be inaccessible from one side, but readings from the IMU can be used to plan a different route to the destination. A Vision system together with GPS, Infra Red or Sonar Sensors and an IMU can be used to create search and rescue robots that can be used in relief operations. To finalize, the IMU can be used to help the robot maintain dynamic stability to some extent but does not serve as a stand-alone unit that can prevent failure during mobile robot exploration in uneven terrain.

REFERENCES