Tip-over Prevention Through Heuristic Reactive Behaviors for Unmanned Ground Vehicles

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ABSTRACT

Skid-steer teleoperated robots are commonly used by military and civilian crews to perform high-risk, dangerous and critical tasks such as bomb disposal. Their missions are often performed in unstructured environments with irregular terrain, such as inside collapsed buildings or on rough terrain covered with a variety of media, such as sand, brush, mud, rocks and debris. During such missions, it is often impractical if not impossible to send another robot or a human operator to right a toppled robot. As a consequence, a robot tip-over event usually results in mission failure.

To make matters more complicated, such robots are often equipped with heavy payloads that raise their centers of mass and hence increase their instability. Should the robot be equipped with a manipulator arm or flippers, it may have a way to self-right. The majority of manipulator arms are not designed for and are likely to be damaged during self-righting procedures, however, which typically have a low success rate. Furthermore, those robots not equipped with manipulator arms or flippers have no self-righting capabilities. Additionally, due to the on-board camera frame of reference, the video feed may cause the robot to appear to be on flat level ground, when it actually may be on a slope nearing tip-over. Finally, robot operators are often so focused on the mission at hand they are oblivious to their surroundings, similar to a kid playing a video game. While this may not be an issue in the living room, it is not a good scenario to experience on the battlefield. Our research seeks to remove tip-over monitoring from the already large list of tasks an operator must perform.

An autonomous tip-over prevention behavior for a mobile robot with a static payload has been developed, implemented and experimentally validated on two different teleoperated robotic platforms. Suitable for use with both teleoperated and autonomous robots, the prevention behavior uses the force-angle stability measure, previously experimentally validated, to predict the likelihood of robot tip-over and trigger prevention behaviors.

A unique heuristic approach to tip-over avoidance was investigated, wherein a set of evasive maneuvers that an expert teleoperator might take are activated when the tip-over-likelihood estimate passes a critical threshold. This control approach was validated on an iRobot *Packbot* as well as on a Segway *RMP 440*. The heuristic laws demonstrated the advantage of alerting operators to a tip-over scenario and gave them more time to correct the situation, as well as the ability to automatically initiate recovery "on the fly".

This research shows promise in preventing dangerous scenarios that could damage a robot and/or compromise its mission, thus saving lives. It further provides a good foundation for follow-on development involving the expansion and integration of the prevention-control algorithms, to include movable payloads, environment manipulation, 2D or 3D look-ahead laser sensing and mapping, and adaptive path planning.

Keywords: Tip-Over Avoidance, Tip-Over Detection, Force Angle stability measure, Shared Control, Unmanned Ground Vehicle, Inertial Measurement Unit, Heuristic Reactive Behaviors

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1. BACKGROUND

The vehicle-stability problem has been studied extensively for mobile platforms ranging in size from small ground vehicles to automobiles to large excavation and forestry equipment. Algorithms exist for determining tip-over likelihood from embedded sensor measurements, and numerous tip-over-prevention controllers have been implemented. Many of these existing methods for preventing tip-over, however, are not applicable to tracked or wheeled vehicles unable to change the locations of their centers of mass. This section describes relevant tip-over-stability measures and previous work in the field of tip-over prevention.

1.1 Robot Stability Detection

Various algorithms have been developed to estimate mobile-robot stability, as for example the Zero-Moment Point (ZMP), the Force-Angle stability measure (FA), and the Moment-Height Stability measure (MHS). The terminology Zero-Moment Point refers to the location on the ground at which the sum of all forces and moments acting on a vehicle can be replaced by a single force.[1] Originally developed for bipedal robots,[2] the ZMP has been extended and applied to mobile robotic vehicles.[3,4] The Force-Angle stability measure evaluates stability based on the angle of the vector sum of the non-supportive or external forces acting at the robot's center of mass.[5] For example, the robot platform shown in Figure 1 is subjected to forward thrust from its driving motors F_m, friction f, and its weight W. The resultant external force is the sum of these forces:

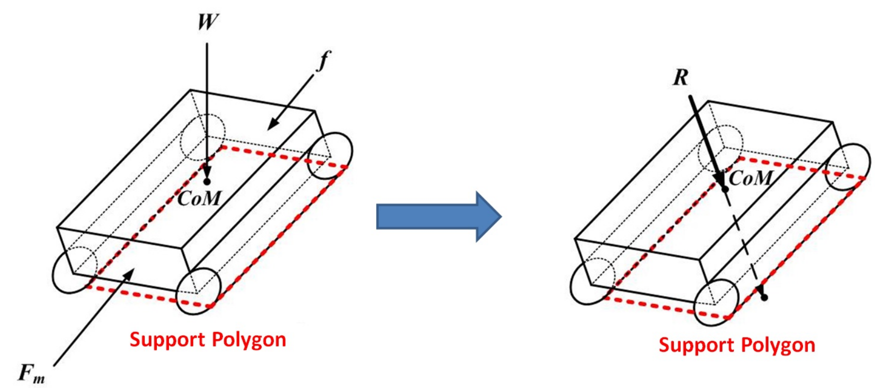

Figure 1. Force Balance Drawing of tracked ground vehicle

$$R = F_m + f + W \tag{1}$$

The tip-over angle is the minimum angle formed between the resultant force vector and the set of vectors pointing from the edges of the convex polygon formed by the ground-contact points to the robot's center of mass, as shown in Figure 2. If the line the force vector follows intersects the ground plane outside the boundaries of the support polygon, the robot has already tipped over. The Moment-Height Stability measure is an extension of the Force Angle Stability measure that includes the effects of the robot's moments of inertia about each edge of the support polygon.[1,6]

Experimental studies have been conducted to determine the most appropriate metric for a given platform and/or application. Roan, et al., applied the three stability metrics described above to data collected from a *Packbot Fido* robot with a constant payload to assess the ability to detect real-world tip-over conditions.[1] Even when applied to noisy data, all three algorithms were deemed suitable for detecting tip-over conditions. In this set of trials, the FA and MHS algorithms providing more effective stability measures than the ZMP algorithm, in some cases indicating tip-over conditions about 3 microseconds before actual tip-over occurred. Since any tip-over-avoidance system must detect when tip-over is eminent, an algorithm that indicates instability before

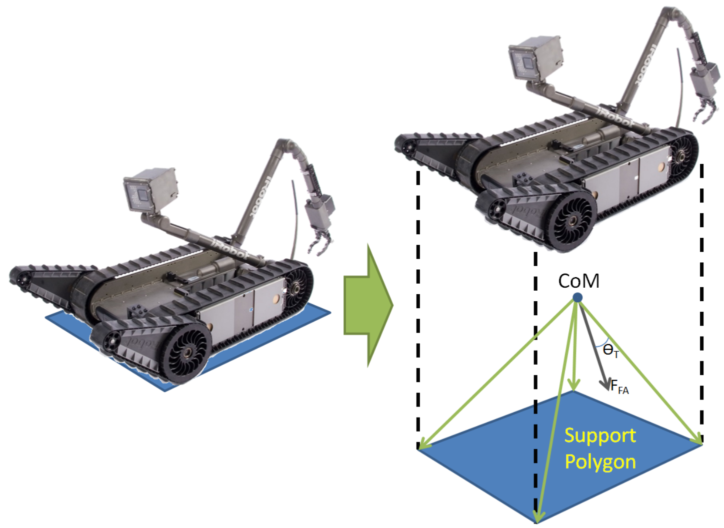

Figure 2. Tip-over angle definition in Force-Angle stability measure

actual tip-over may be more desirable for implementation.

1.2 Tip-over Prevention Control for Mobile Robots

Algorithms and control laws have been designed to detect and prevent rollover in both passenger vehicles and mobile robots.[7–13] Peters and Iagnemma modify the FA metric for application to rollover detection of high-speed mobile robots traversing various terrains.[7] Ackermann and Odenthal prevented vehicle rollover using a controller that sets a small auxiliary steering angle using an onboard actuator, in addition to the driver's steering angle.[8] Krid and Benamar added a controllable anti-roll torsion bar and used a model-based predictive controller to maintain roll stability.[9] Active steering and braking control has been used by several researchers to prevent rollover and wheel liftoff; see for example.[10,11] Bouton, et. al, use *Lateral Load Transfer* to predict rollover of off-road vehicles, then limit vehicle velocity.[12] Arndt, et. al, developed a control law to stabilize roll angle that is capable of driving a small four-wheel robot in a two-wheel balanced state down a hallway.[13] This work is focused on vehicles and robots with suspension systems and not readily applicable to tracked vehicles.

Tip-over avoidance has been incorporated into path-planning and hazard-avoidance algorithms for mobile robots moving at both low and high speeds over rough terrain.[14–16] In these methods, predicted tip-over states are excluded from the feasible trajectories in the path-planning algorithms, and hence tip-over is avoided. These methods work well when predefined paths, waypoints and/or end goals are defined, but are not applicable to tele-operated robots that simply react to the operator's commands.

Stabilization of moving manipulators has been studied for many years. Dubowsky and Vance developed a planning method that permits quick execution of manipulator tasks without destabilizing the mobile robotic base.[17] Manipulator tasks were accomplished while the mobile base was static. Hootsmans and Dubowsky investigated the dynamic interaction between the manipulator and the mobile base that accounted for the suspension and tire/ground interactions, and developed an extended Jacobian transpose-control algorithm to improve manipulator performance.[18] Again, the mobile base was to remain stationary during manipulation. Rey and Papadopoulos, developed a tip-over prevention algorithm based on the FA measure that moved the mobile base of a large forestry vehicle, interacting with the environment to compensate for destabilizing forces and moments.[19] Later research considered stabilization of mobile manipulators while both the base and manipulator are moving.[3,4,20,21] In this work, the robots under consideration have the ability to change the location of their centers of mass by moving both the driving wheels and the manipulator arms. Related work applies this strategy to mobile robots without manipulators that retain the ability to change the locations of their mass centers, such as rocker-bogie style rovers with articulated suspensions and tracked vehicles with flippers.[14,21] The ground vehicles studied in this work do not have manipulators or other means of redistributing their payloads once deployed, so such tip-over prevention behaviors are not applicable at this time

Control algorithms have been developed to stabilize non-reconfigurable robots traveling along inclined trajectories such as staircases.[22] Terupally, Zhu and Williams focused on ascending inclined planes with rough surfaces (i.e. stairs) at the angle of steepest ascent, thus making the problem two-dimensional. Dynamic forces causing changes in roll-and-pitch angular rates were not considered, nor were changes in terrain roughness.

1.3 Current Research and Sensor Suite

In this research, the robot is assumed to have a fixed payload with no mobile manipulator arm nor flippers, so its geometry is assumed fixed and its only actuators are the drive motors. Therefore it is not capable of shifting the location of its center of mass and the algorithms utilizing payload redistribution are not applicable. This problem has not been considered for cases in which stability on an arbitrarily inclined slope with varying terrain is desired. Thus, this research focuses on stabilizing a robot on an arbitrary sloped surface with widely varying surface characteristics.

For this research, an inertial measurement unit (IMU) payload was installed on an iRobot *PackBot*, as shown in Figure 3. The IMU payload contains the processor to run the tip-over and control algorithms, GPS, Ethernet for wireless communication, and the MicroStrain *3DM-GX3*® inertial sensor. The data obtained from the latter sensor include, pitch, roll, yaw, pitch rate, roll rate, yaw rate, and accelerations (x, y, z). This data was used by the tip-over-detection algorithms to give a measure of the likelihood of tip-over, as well as by the developed control algorithms described in this paper.

(a) 

(b) 

Figure 3. (a) IMU payload on an iRobot *PackBot*, (b) MicroStrain *3DM-GX3*® inertial sensor. (Figure courtesy of www.microstrain.com)

2. HEURISTIC TIP-OVER CONTROLLER DESIGN

Here a simple intuitive approach to control design was taken, in which the actions that an expert operator may take to avoid tip-over were analyzed and programmed into software. These evasive actions are activated when the tip-over stability measure has exceeded a critical threshold. The advantage to programming these behaviors in software is that the computer will, in general, react more quickly than a human, thus the evasive maneuvers can initiate before getting past the point of no return. Two heuristic behaviors were developed: *Turn-To*, and *Slow-Down*. Of these behaviors, the *Slow-Down* behavior is the least invasive, allowing more time for the operator to navigate the environment, while the *Turn-To* behavior overrides operator input to ensure the highest stability.

2.1 *Turn-To* Behavior

The *Turn-To* behavior rotates the robot so that the direction of likely tip-over points to one of the four corners of its support polygon, the polygon defined by the points of contact with the ground as shown in Figure 2. Assuming that the center of mass is near the robot's geometric center, turning the robot so that the projection of the vector sum of the destabilizing forces points towards one of the four corners results in the pose of greatest stability. Consider the sum of the destabilizing forces on the robot's center of mass as shown in Figure 4. In the

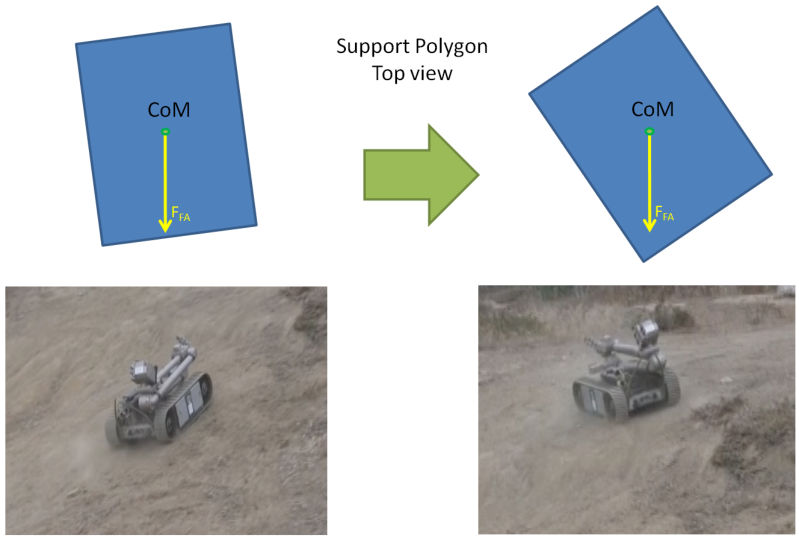

Figure 4. *Turn-To* Behavior example

configuration on the left, this force is directed toward a point below the robot body, near its edge and hence it is near tip-over. By rotating the robot so that the sum of destabilizing forces is directed to a point beneath the robot further from any of its support-polygon edges, the robot is less likely to tip-over as illustrated on the right. The decision as to which corner to turn toward is decided based on the direction of the tip-over vector as referenced from the forward axis of the robot. The *Turn-To* behavior rotates the robot according to the following convention:

- If the tip-over direction is between 0 and 90 degrees, rotate so the summation force vector aligns with the front-right sprocket
- If the tip-over direction is between 0 and -90 degrees, rotate so the summation force vector aligns with the front-left sprocket.
- If the tip-over direction is between 90 and 180 degrees, rotate so the summation force vector aligns with the right-rear sprocket.
- If the tip-over direction is between -90 and -180 degrees, rotate so the summation force vector aligns with the left-rear sprocket.

as shown in Figure 5.

2.2 *Slow-Down* Behavior

The *Slow-Down* behavior monitors the measure of instability and slows the platform proportionally. This behavior is inactive below a configurable user-defined threshold and slows the robot down more as the robot gets closer to tipping over. This approach automatically reduces the effects of dynamic forces on the system, as well as gives

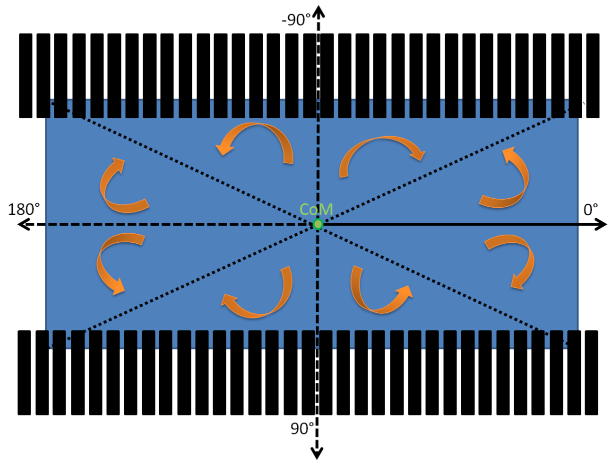

Figure 5. *Turn-To* rotation conventions

the operator a notification and an opportunity to correct the situation before an undesired result is reached. The scaled commanded velocity is defined as:

$$\hat{v_c} = ((100 - T)/100) * (v_c * S) \tag{2}$$

where $\hat{v_c}$ is the scaled input forward velocity, T the stability measure, v_c the user-commanded forward velocity, and S a configurational scaling factor, generally 1 and changed only for experimental development.

3. RESULTS

In this section we discuss the results for tip-over detection and the reaction-behavior algorithms running in real time on two different platforms; a tracked robot (iRobot *PackBot*) and a wheeled robot (Segway *RMP 440*). Each robot has an IMU payload which communicates to the robot and runs the algorithms. The user controls the robot through the *Multi-robot Operator Control Unit (MOCU)*, shown in Figure 6, which displays an avatar, shown in Figure 7, that warns the user of a possible tip-over scenario and notifies the user when the reactive behavior is active. Note that because the behaviors are based on instantaneous and prior-position data only, they do not account for unseen objects in the robot's pathway or unpredictable terrain, which may cause a tip-over scenario regardless of the reactive behavior.

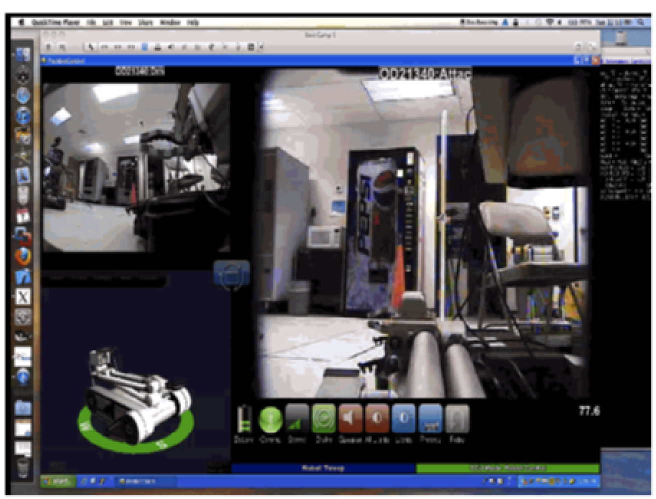

Figure 6. *MOCU* display for *PackBot*

Figure 7. Avatar display in *MOCU*: (right) stable, (left) warning tip-over

3.1 Tip-Over Detection Verification

As described in Section 1, three algorthims were used for tip-over detection: the Force-Angle (FA), Zero-Moment Point (ZMP), and Moment Height (MH) stablity measures. Previous numerical research suggested that of the three measures, the Force-Angle stability measure provided the most advance notice in warning the user.[1] Figure 8 shows real-time data on a *PackBot* which demonstrates that the Force-Angle stability measure does indeed produce the results as expected in Roan, et. al.[1] In this scenario, while no reactive behaviors were active, the dashed line at 0.35 denotes when the reactive behavior would turn on to prevent a possible tip-over. Clearly, we can see that at 60 seconds the FA algorithm would activate prevention measures 2 seconds before the ZMP algorithm, while the MH algorithm never reaches the triggering threshold. At 107 seconds, the FA algorithm would again activate reactive behaviors first, followed by the MH about 2 seconds later at 109 seconds, and ZMP 3 seconds after that at 112 seconds. In this scenario, the robot actually encounters a tip-over around 113 seconds. Note that all three measures agree on when the robot has tipped over.

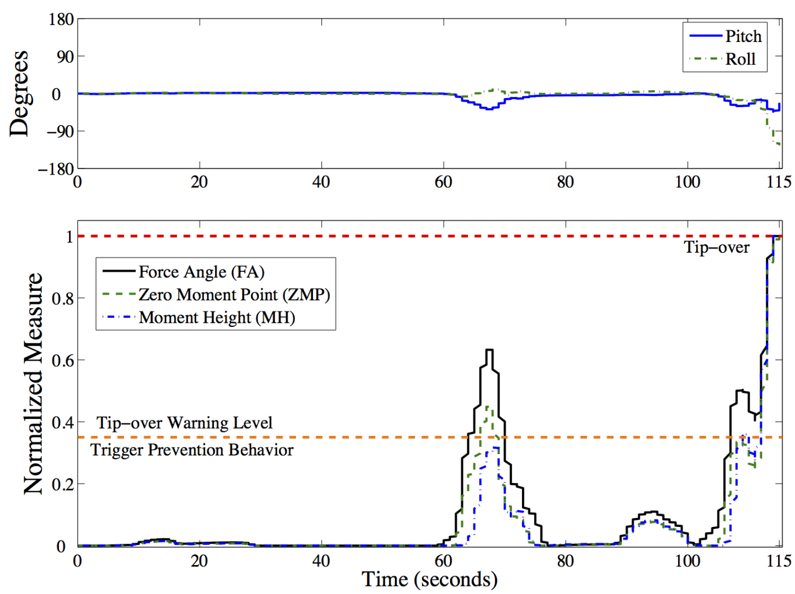

Figure 8. Tip-over detection measures

The tip-over detection algorithms have many user configurable parameters: the threshold or warning level for triggering the reactive behavior, W_L, a minimum time above that threshold to reduce false detection, t_{min}, and physical properties, such as mass of robot, m, center of mass, cg_x, cg_y, cg_z, and physical dimensions of the robotic platform. For our testing, $W_L = 0.35$, $t_{min} = 0.1$, and the physical properties are based on the robot in use.

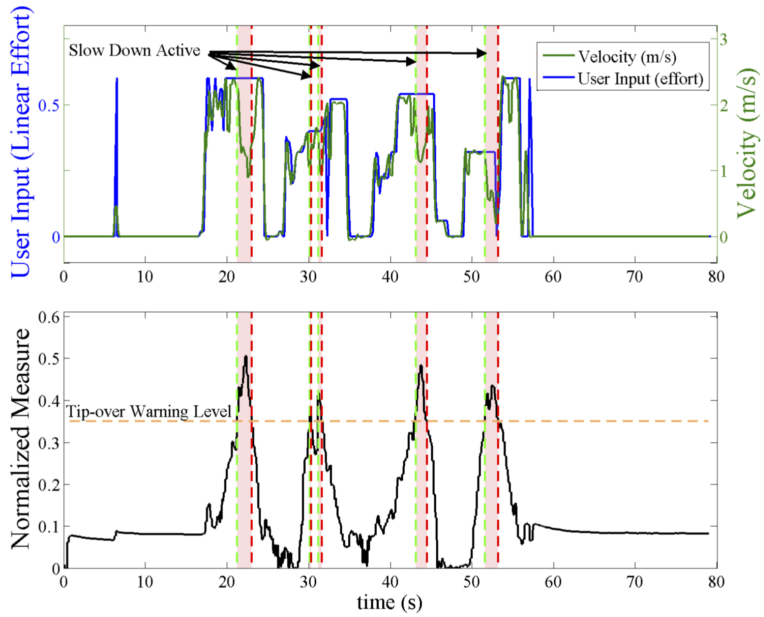

Figure 9. *Slow-Down* behavior active. (Top) User input for linear effort vs. velocity of robot, (Bottom) normalized tip-over measure showing a tip-over warning level of $W_L = 35$.

Given $W_L > 0.35$ and $t_{min} > 0.1$, the reactive behaviors described in Section 2 become active until $W_L < 0.35$. In the following sections, the results demonstrate how the reactive behaviors benefit the stability of the robot.

3.2 Heuristic Behavior Control

Both the *Turn-To* and *Slow-Down* behaviors exhibited positive results. As the name suggests, the *Slow-Down* behavior reduces the speed of the robot when the detection parameter is greater than W_L for t_{min}, as described in section 2.2, and shown in Figure 9. By slowing the robot down, not only does it give the operator more time to correct the scenario, but reduces the dynamic effects of the powered actuators when driving on flat or uphill terrain. However, *Slow-Down* does present a risk when driving downhill, as braking may actually increase the dynamic forces and cause the robot to flip over forwards. To address this issue, the *Slow-Down* control was modified into a Dynamic-Drive heuristic behavior for testing, which applied *Slow-Down* when going uphill, but conversely increases speed when driving downhill. While this reactive behavior showed promise to increase the dynamic stability when driving downhill, it also decreased the reaction time and capabilities of the user. Thus it was apparent that leaving the *Slow-Down* behavior as-is, or activating it only on flat or uphill terrain provided the best results even with the evident risks during downhill driving.

Figure 9 shows the difference between the user input and the actual velocity of the robot. When the first tip-over warning was triggered at 22 seconds, we notice a tracking separation between the desired and actual velocity, with the actual velocity significantly lower. The disparity between the actual and desired velocity continues until the tip-over parameter has decreased below the behavior initiation threshold W_L as seen in the lower half of Figure 9. The *Slow-Down* initiation and velocity correction happened four times during this specific test, safely protecting the robot from a tip-over scenario. Also tested was a max-speed-control behavior that limited the

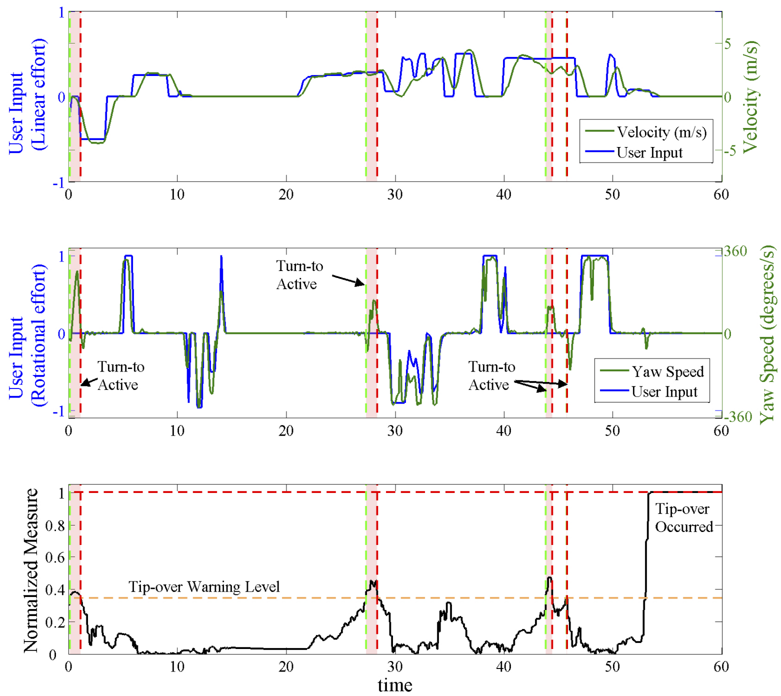

Figure 10. Results with *Turn-To* behavior active. The top graph shows user input for linear effort vs. yaw speed of robot, the middle shows user input for rotational effort vs. velocity of robot, and the bottom graph shows the normalized tip-over measure showing a tip-over warning level of $W_L = 35$.

robot's speed when the detection parameter was triggered, i.e. $W_L > 0.35$. This method is a slightly different implementation of the *Slow-Down* behavior, as the degree to which the robot slows down is specified as a max speed. In the *Slow-Down* behavior, the speed of the robot is specified based on the current detection parameter. A max-speed limit would allow the user to speed up and slow down within the range below the max-speed limit, which could potentially give the user some extra mobility to correct the situation. It may also be possible that the robot is already driving below that max speed when the behavior gets triggered, in which case a max-speed limit would not have any effect. Because of this possibility, the *Slow-Down* behavior continues to specify the velocity inversely to the tip-over parameter.

The *Turn-To* behavior successfully turns the robot such that the tip-over vector points to the appropriate corner of the robot for increased stability as described in Section 2.1. The *Turn-To* behavior was found to behave well when at low speeds. Figure 10 shows the *Turn-To* behavior activating when the tip-over parameter rises above the triggering threshold W_L, and confirmed by the difference between the desired-rotational-effort input and the actual yaw speed, as seen in the middle figure. Subsequently, the normalized tip-over parameter decreases below the threshold, confirming that the robot turned in the correct direction. One large potential drawback of the *Turn-To* reactive behavior is that the behavior can override the user's input and potentially cause a tip-over scenario by encountering an obstacle the operator was specifically trying to avoid. As seen in Figure 10, the robot encountered a tip-over scenario at 55 seconds, which it wasn't able to avoid. The terrain at this specific moment was such that turning actually made the robot encounter an obstacle, and the additional lateral force on the treads due to the skid-steering at low speed caused the tip-over.

4. CONCLUSION

In this research, an autonomous tip-over prevention behavior for a mobile robot with a static payload was developed, implemented and validated experimentally on two different tele-operated robotic platforms. The behaviors are suitable for use with both tele-operated and autonomous robots. The prevention behavior uses the Force-Angle stability measure, experimentally validated previously,[1] to predict the likelihood of robot tip-over and to trigger prevention behaviors.

A unique heuristic approach to tip-over avoidance was investigated, wherein a set of evasive maneuvers that an expert teleoperator might take are activated when the tip-over-likelihood estimate passes a critical threshold. This control approach was validated on an iRobot *Packbot* as well as on a Segway *RMP 440*. The heuristic laws demonstrated the advantage of alerting operators to a tip-over scenario and gave them more time to correct the situation, as well as the ability to automatically initiate recovery "on the fly".

This research shows promise in preventing dangerous scenarios from occurring, thus saving lives. It provides a good basis for follow-on research involving the expansion and integration of the prevention control algorithms to include movable payloads, environment manipulation, 2D or 3D look-ahead laser sensing and mapping, and path planning, among others.

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