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Mobile Manipulator Stability Measurements

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1. Abstract

Mobile manipulators are being marketed for material handling and other tasks. Manufacturers suggest that the stability of the vehicle is best when the onboard loading tapers the centroid to the center of the wheelbase as the payload height increases. Experiments were performed at the National Institute of Standards and Technology (NIST) that verify this notion on an Adept Lynx mobile robot with onboard Universal Robots UR5 manipulator. Results show that cantilevered loads near the payload top height cause vehicle instability during navigation that can roll the vehicle and cause off-path navigation. This paper describes the stability experiments and results.

Keywords: mobile manipulator, stability, optical tracking, static and dynamic performance measurements

2. Introduction

Stability of wheeled vehicles is critical to ensure safe and reliable performance of vehicles used in industrial, healthcare, response, and other industries. Focusing on industrial vehicles, International Organization for Standardization (ISO) 1074 [1] stability tests apply to safety of fork lifts. The Industrial Truck Standards Development Foundation (ITSDF) B56.8 [2] standard describes two static tests that require a tilt table and dynamic tests called speed tests. Lessons can also be learned from standards for vehicles used in other industries. For example, industrial vehicle stability tests can apply dynamic ISO 7176 ramp wheelchair tests [3,4,5] to mobile robots used on level surfaces. Similarly, industrial robot offset-load tests discussed in ISO 9283 [6] can also be applied to industrial vehicle stability tests.

To demonstrate stability issues that could occur with mobile robots, a fully-loaded Adept Lynx[1] mobile robot was tested at the National Institute of Standards and Technology (NIST) using two different test courses – 90° turn and circle – to measure stability when no load and offset loads were applied to the vehicle. The offset load's location from the Lynx center of gravity (CG) was selected to be on the outside of the vehicle causing the most vulnerable instability during turns. Additionally, the distance to the CG was randomly selected to be near the midpoint UR5 manipulator length where potentially many manipulator operations occur.

The Lynx manual recommends that the CG for Lynx payloads be within the wheel footprint and tapered towards the vehicle centroid as the load is raised along the z-axis. Figure 1 shows a drawing of the Lynx with the NIST structure and Universal Robot UR5 mounted onboard. The red lines taper up towards the vehicle centroid and also to the top left (i.e., red box cantilevered away from the centroid). The cantilevered box indicates an approximate area that may include the offset payload of the UR5 robot with its gripper when used at a static mobile robot location. However, the stability when navigating from one location to another with an offset load (such as the UR5 with gripper) is unknown. For example, should the robot arm

[1] Disclaimer: Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

extend beyond the mobile robot wheelbase while moving between locations, instability could occur.

The approximate loads for each component or set of components are also shown. The total loading is estimated at 52.3 kg (115 lbs) with a measured vehicle weight, including payload structure and manipulator with controller, totaling approximately 136.4 kg (300 lbs). In Figure 1, the mobile manipulator is shown next to the reconfigurable mobile manipulator apparatus (RMMA) for relative size scaling. The RMMA is being developed to measure various aspects of mobile manipulator performance [6]. Tests are planned to measure the mobile manipulator performance using the RMMA. Unlike an automatic guided vehicle (AGV) that uses points and segments to navigate, the Adept plans and navigates paths that may be different from the expected plan or path. Therefore, it is critical for this advanced mobile manipulator to perform without instability issues when navigating to, accessing, and docking with the RMMA.

Two stability experiments are described in the next section, followed by results of the experiments. Conclusions, references, and an appendix follow with clauses from vehicle safety standards that discuss vehicle stability.

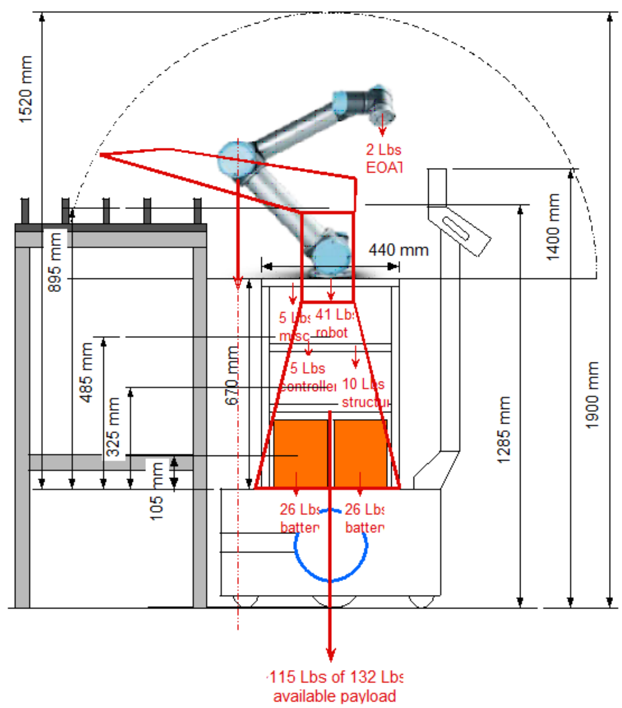


Figure 1 – Drawing of the Adept Lynx with onboard UR5 robot and support structure and highlighting (red boxes) the approximate loads of each component and the sum of all components. The left gray drawing depicts the RMMA for size comparison to the mobile manipulator.

3. Experiments

An anti-tip wheel structure (i.e., similar to bicycle training wheels) was added to the Lynx extending 310 mm on both the right and left sides. The distance was chosen to ensure anti-tip while remaining a lightweight addition to the vehicle. The wheels were raised 13 mm above the floor and mounted to angled aluminum while not obstructing the front obstacle detection laser detection and ranging (LADAR) sensor. Two experiments were performed to demonstrate mobile manipulator instability issues. The UR5 remained in a compact configuration (see Figure 1) and within the Lynx wheelbase to prevent potential damage to the UR5. Figure 2 shows the experimental vehicle setup with an added bar simulating the robot arm and extending added weights 790 mm (31 in) beyond the mobile manipulator CG.

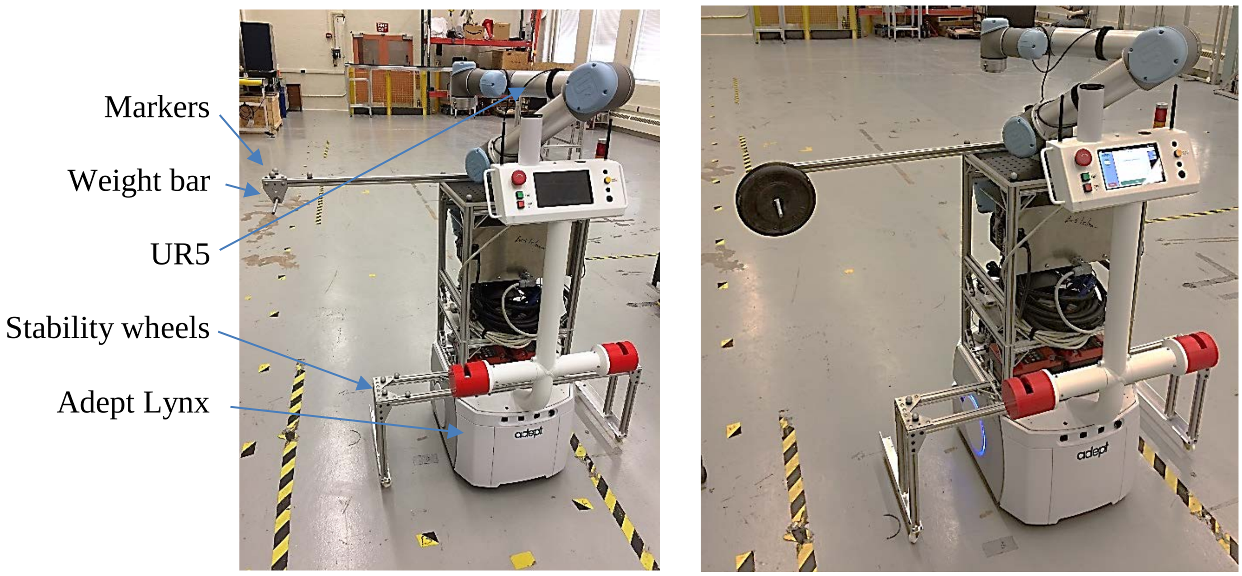


Figure 2 – Adept Lynx with added stability wheels and weight bar and no added weight (left) and added 9 kg (20 Lbs) weight (right).

Initially, two static measurements were performed to measure the vertical, without-payload Lynx with and without tilt. When stationary, the vehicle was tipped by the operator until the anti-tip device wheels touched the floor. These tests were used as comparison to the dynamic test data captured when the Lynx navigated the programmed paths.

Tests included navigating at 1.5 meters per second (m/s) (4.9 feet per sec), along a preferred (according to the Lynx controller) straight line path of approximately 10 m long followed by a 90° right turn to a stop point approximately 3 m from the turn, rotating in place at the stop point, and then returning to the start position along the same path. Figure 3 (left) shows the path programmed on the Lynx controller. A pre-start point was programmed to be prior to the start point to allow measurement at the start point. The preferred path (green dotted line) is used by the controller so that the vehicle does not navigate directly to the end from the start point. Three trials were performed with the following cantilevered loads: 0 kg, 4.5 kg (10 lbs), and 9 kg (20 lbs).

A second experiment was performed using an approximated circle path. The circle was designed using several preferred straight lines since the controller does not provide arc lines. A paper circle was cut out and taped to the controller's screen and several straight lines were then used to create a preferred path in an approximated circle. The taped circle was removed and clock-face goals of 3 o'clock, 9 o'clock, and 12 o'clock names were given to their relative clock positions so that quarter, half, three-quarter, and full arcs could be navigated. To ensure that the vehicle followed the path, restricted (orange solid) lines were drawn inside and outside the circle. An end goal was also placed beside the start location and used as the pre-start point for tests. Due to the controller limits, only one loop from start to end goal (6 o'clock points) could be performed for each trial.

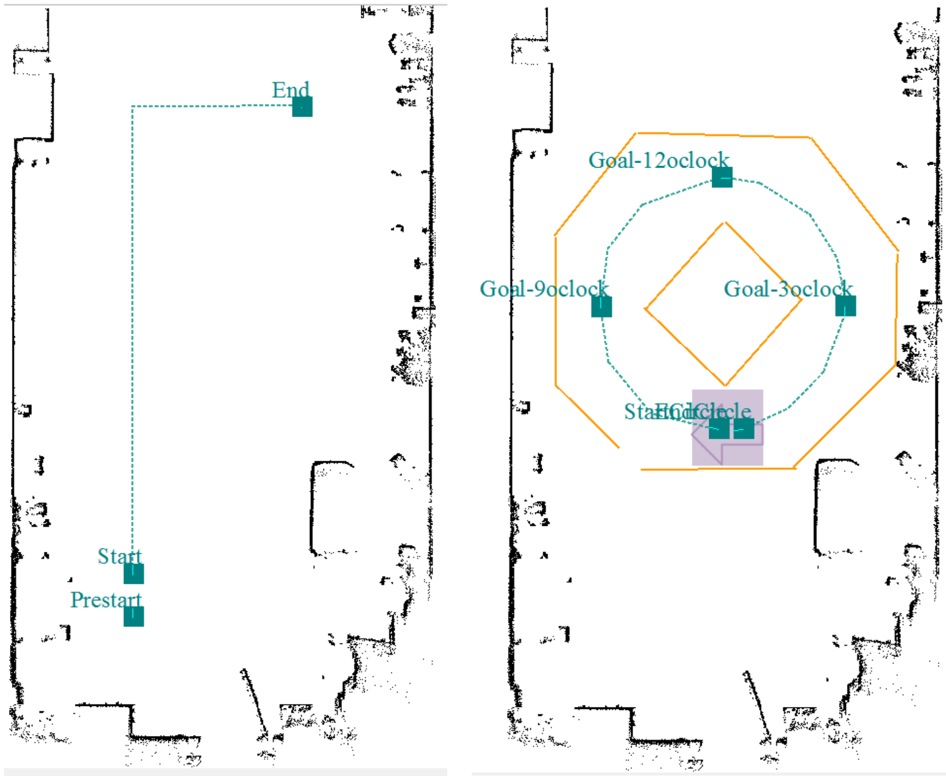


Figure 3 – Maps showing the preferred path (green dotted lines) for the Lynx to navigate with 90° turn path (left) and circle path (right). Forbidden lines (orange solid) were drawn outside and inside the circle path so that the Lynx stayed on the preferred path. A purple direction arrow was drawn across the start and end points to ensure the vehicle navigates in one direction from start towards the end of the circle.

4. Results

Three markers measured by the optical tracking system were added to the top of the bar (WeightBar) that supported added weights cantilevered from the robot. Static height measurements of the bar using a tape measure were performed for six locations along the 90° turn path only since the same floor regions were used for both experiments. Height measurements were performed from floor to the WeightBar when the vehicle was tilted so that the stabilizer wheels touched the floor. Table 1 shows: the added weight to the WeightBar, the mean of six static distance to floor from the WeightBar measurements along the 90° path, the difference between the 0 kg weighted distance and the 4.5 kg and 9 kg weighted distances, the standard deviation of the six measurements, the tilted vehicle distance from the markers to the floor for no load, and the difference from tilted to normal vehicle profile vertical distances for no load. The difference was most likely caused by the bar bending due to the weight and/or that the added load acts like a damper on the bar (as noted by the higher standard deviation for 0 kg vs the 4.5 kg and 9 kg trials).

Table 1 – Static measurements of the upright and tilted vehicle, with cantilevered bar, to the floor.

Weight	Mean of Six Measurements along 90° path Static distance to floor	Difference from 0 kg distance	Std Dev of Six Measurements	Single measurement of tilted vehicle WeightBar to floor	Tilted vehicle to normal profile vehicle vertical difference
0 kg	1133 mm	0 mm	4.2 mm	1096 mm	37 mm
4.5 kg	1128 mm	5 mm	3.7 mm	1095 mm	33 mm
9 kg	1123 mm	10 mm	3.7 mm	1092 mm	31 mm

For experiment 1, the Lynx ramped up to full speed, or 1.5 m/s, for approximately 3 m to 5 m and then decreased speed to approximately 0.5 m/s to 0.75 m/s during the 90° turn. The planned path from the vehicle controller is shown in Figure 4 (a). The velocities were monitored from continuous vehicle controller status updates by the researcher controlling the Lynx. The straightest path near the preferred path occurred when there was no additional cantilevered weight added. For the 9 kg load, during at least one of the three trials, the vehicle meandered back and forth approximately 100 mm side to side along the path, and in all of the trials the vehicle deviated from the preferred path after the turn in either direction.

For experiment 2, five each of no load, 4.5 kg, and 9 kg offset loading trials were performed and measured using an optical tracking system. During all trials, the Lynx ramped up velocity from the start position to approximately 1.2 m/s for approximately one quarter of the circle and then decreased speed when nearing the goal until the goal was reached. The planned paths from the vehicle controller are shown in Figure 4 (b, c). The velocities were monitored by the researcher controlling the Lynx. With no added offset loading, the vehicle performed well executing a nearly circular path along the series of straight paths that made up the circle. A noticeable difference in path following occurred with both of the 4.5 kg and 9 kg offset weights cantilevered from the vehicle, where erratic behavior (e.g., traversed from side-to-side across the path or was completely off the path) sometimes occurred due most likely to the vehicle tilting.

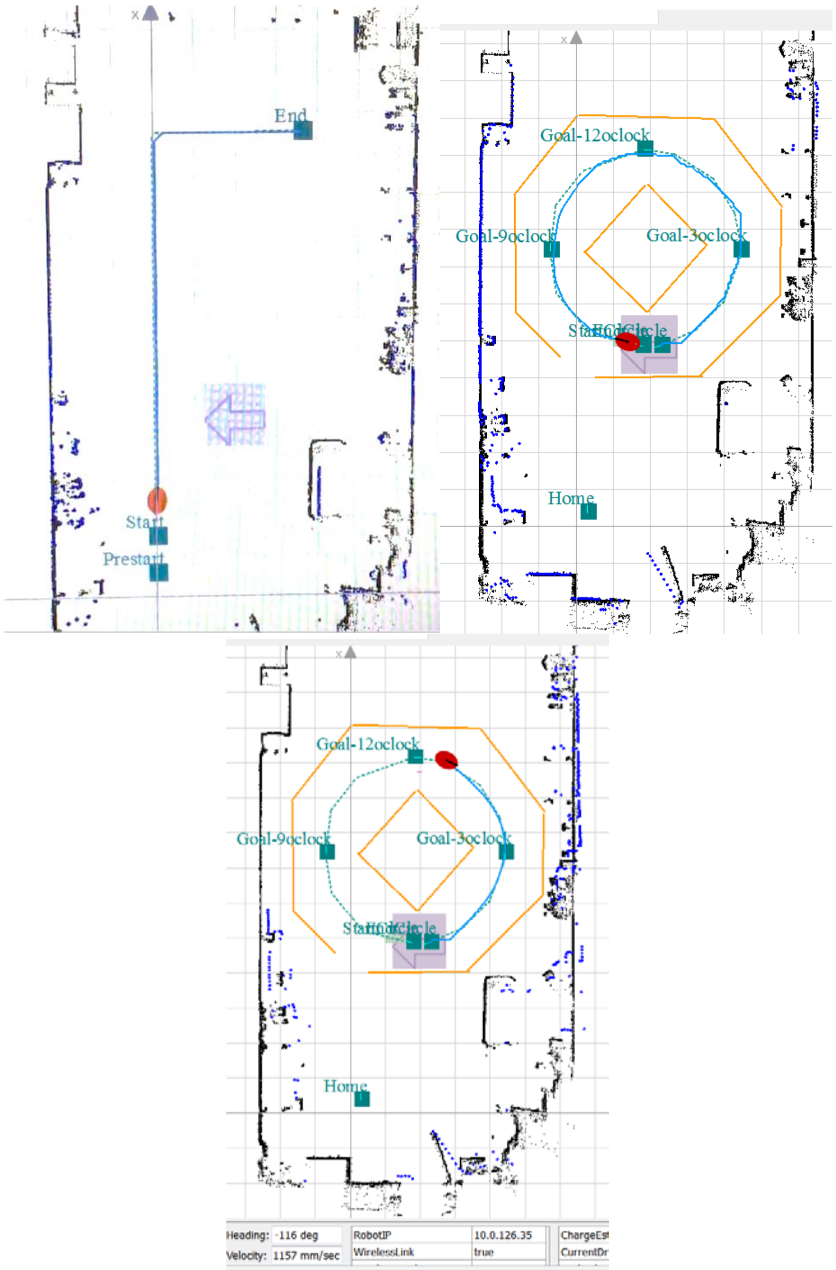


Figure 4 – Lynx controller planned paths (blue lines) for the (a) experiment 1 90° turn and (b and c) experiment 2 circle where (b) shows the initial full loop plan and (c) shows the approximate half circle to goal plan and the Lynx velocity at 1.157 mps (bottom).

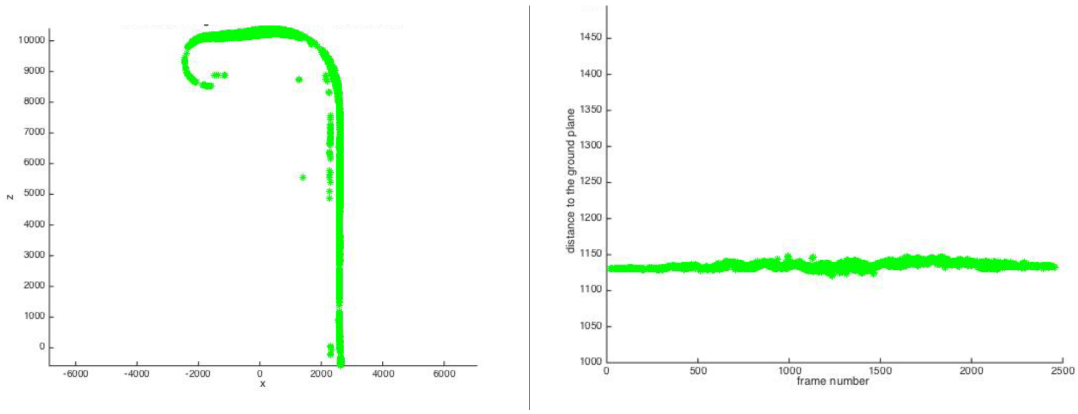
Statistical analysis of the measurement data sets (five trials for each added weight) for the two experiments using the tracking system showed that the height between the WeightBar and the floor varied as follows:

Table 2 – Results from tracking system of dynamic vehicle stability

Weight	Mean Distance of WeightBar to the Floor	Std Dev of five runs for distances to the floor plane	Minimum Distance of WeightBar to the Floor
90° turn data			
0 kg	1134 mm	0.8 mm	1121 mm
4.5 kg	1128 mm	1.4 mm	1111 mm
9 kg	1120 mm	2.7 mm	1090 mm
Circle data			
0 kg	1171 mm	0.7 mm	1107 mm
4.5 kg	1170 mm	1.4 mm	1101 mm
9 kg	1165 mm	0.8 mm	1083 mm

For experiment 1, 90° turn, the results show that the vehicle is tilting towards the weighted end when the 4.5 kg weight is added since there is high uncertainty for the 4.5 kg trials, although the height is the same as for the 0 kg trials. The 9 kg trials also showed tilt with relatively high uncertainty and smaller distances from the floor than for the 0 kg trials. For experiment 2 - circle, the results show that the height uncertainty is more consistent for the 9 kg trials. However, the minimum distance of WeightBar to the floor plane varies during a measured location within trials of 18 mm and 24 mm with respect to the 0 kg loaded trials. This demonstrates vehicle tilting during the circle experiment.

In both experiments, the addition of offset loads provided not only tilting, but also erratic vehicle swerving as the controller attempted to realign the vehicle to the preferred path. Figures 5 and 6 show several plots of data from the tracking system and of the distance change from the weight to the floor during selected experiment 1 and experiment 2 trials, respectively. In experiment 1, the vehicle followed the preferred path much closer when there was no added weight. However, as shown in Figure 5 (b and c), when 4.5 kg (10 lb) or 9 kg (20 lb) was added to the weight bar, the vehicle did not follow the preferred path, with some weaving with the 4.5 kg weight and much more weaving with the 9 kg weight when navigating along the long path. The vehicle then overshot the 90° turn and short path and headed to the goal without following the path.



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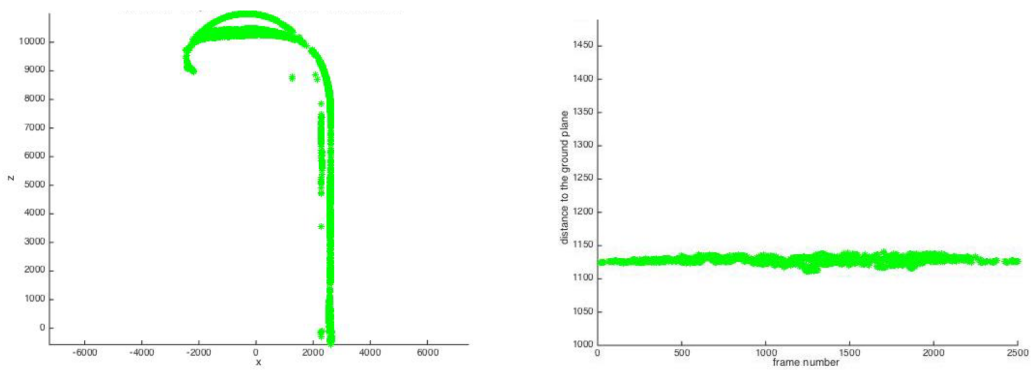

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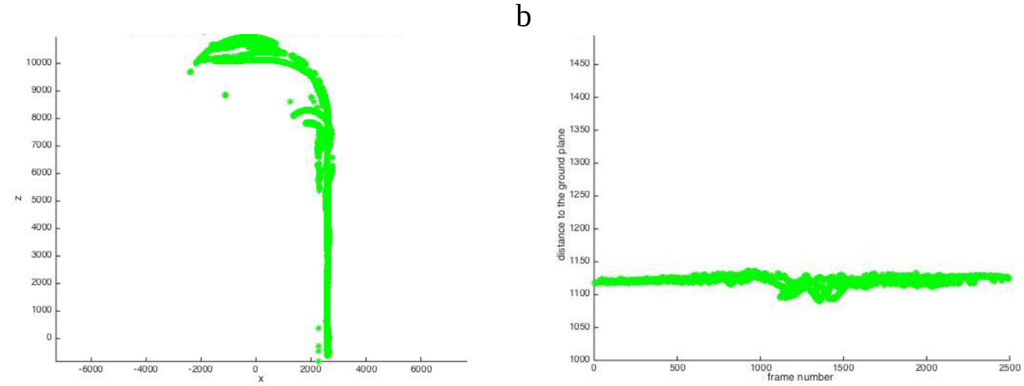

c

Figure 5 – (left) Two dimensional plots of data from the tracking system and (right) distance change plots from the weight to the floor during selected experiment 1 trials for each weight: (a) 0 added weight, (b) 4.5 kg added weight, (c) 9 kg added weight. All units are in mm.

Experiment 2 plots are shown in Figure 6 where Figure 6 (a and b) show fairly circular path following. However, Figure 6 (c) shows that when 9 kg (20 lb) was added to the weight bar, the vehicle deviated further from the preferred circular path.

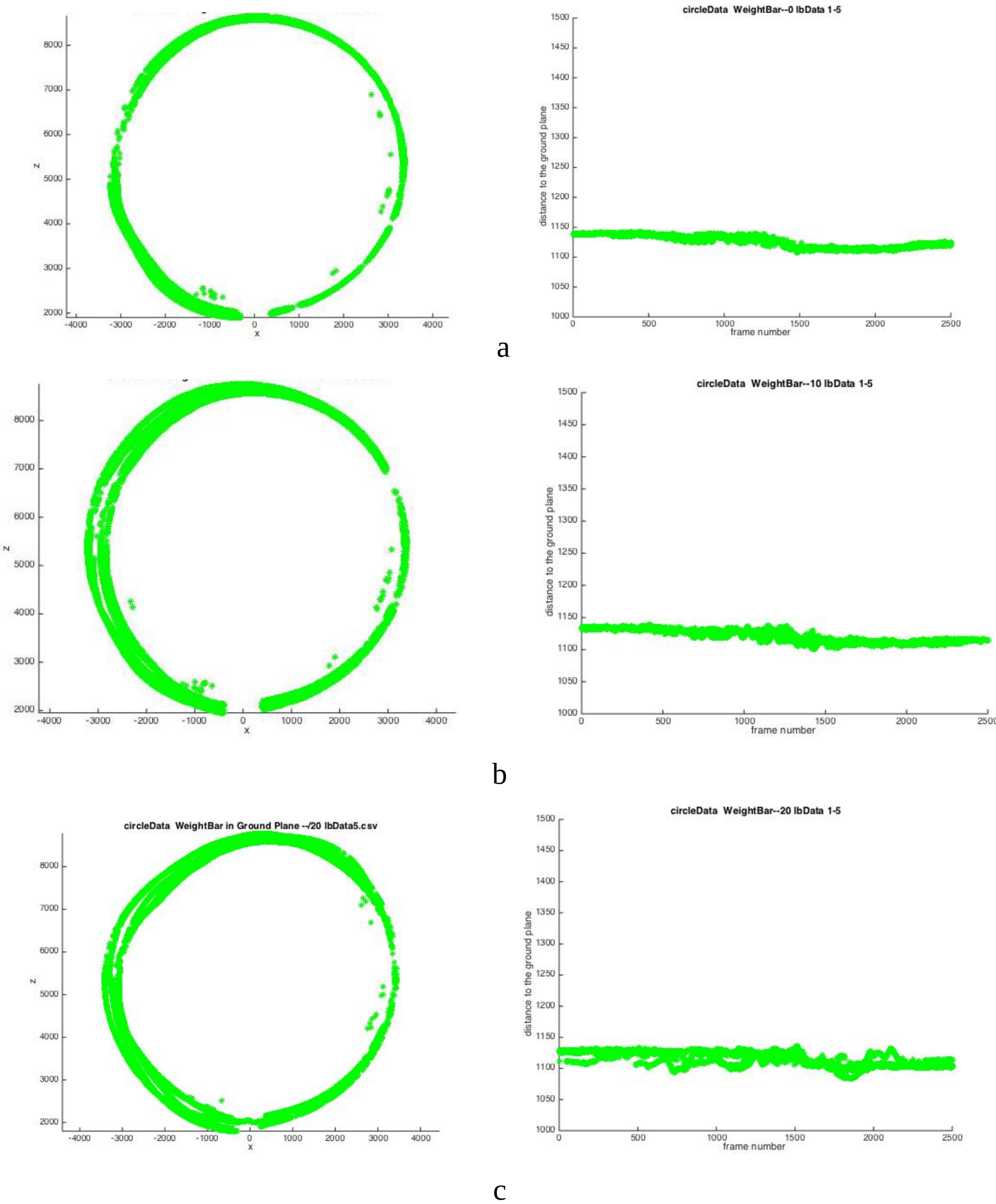

Figure 6 – (left) Two dimensional plots of data from the tracking system and (right) distance change plots from the weight to the floor during selected experiment 2 trials for each weight: (a) 0 added weight, (b) 4.5 kg added weight, (c) 9 kg added weight. All units are in mm.

5. Conclusions

Stability tests were performed using an Adept Lynx mobile robot outfitted with stability wheels and weight bar with weights. Tests were performed commanding the vehicle to run at full speed (i.e., 1.5 m/s). During the experiment 1, 90° turn tests, the vehicle achieved full speed and turned 90° to a short path at nearly half speed. During the experiment 2, circle tests, the vehicle achieved approximately 1.2 m/s top speed nearly halfway around the circle. In all trials during both experiments, the no-load trials provided no measured tilting onto the stabilizer wheels. However, some tilting or instability occurred with the 4.5 kg offset load and much more occurred with the 9 kg offset load, indicating that the vehicle would tip over without the use of stabilizer wheels. Also, the additional offset loads provided not only tilting, but also erratic vehicle swerving as the controller attempted to realign the vehicle to the preferred path. Hence, the current ≈ 52 kg payload, total ≈ 132 kg vehicle, provides reliable vehicle stability during maximum velocities for the height of the onboard UR5 only when the UR5 is stowed. Should the UR5 not be stowed and cantilevered outside of the Lynx wheelbase, vehicle speeds that near maximum may cause vehicle instability. Potentially, vehicles are equipped with software interlocks that won't allow the cantilevered payload situation. Some recommended test methods for standards development can include: 1) the experiments performed, or for simplicity and cost savings, 2) contact switches combined with a computer to log stabilizer bar contact with the floor during tilt, 3) or video of when a light turns on from a contact switch during stabilizer bar contact with the floor. Future tests should also consider the stability effects of the manipulator picking up or applying loads when cantilevered from the mobile base.

6. Acknowledgements

The authors thank Matt LaFary from Omron Adept Technologies for his guidance in developing preferred vehicle paths.

7. References

1. IS0 1074: 1991 (E) Counterbalanced fork-lift trucks – Stability tests, second edition.
2. Industrial Truck Standards Development Foundation, B56 Standards, www.itsdf.org, accessed Dec 13, 2016.
3. ISO 7176-1:2014 Wheelchairs -- Part 1: Determination of static stability 60.60 ISO/TC 173/SC 1
4. ISO 7176-2:2001 Wheelchairs -- Part 2: Determination of dynamic stability of electric wheelchairs
5. Joshua Johnson, Roger Bostelman, "Static and Dynamic Stability Performance Measurements of the HLPR Chair/Forklift", NIST Interagency/Internal Report (NISTIR) – 7667, March 03, 2010.
6. Roger Bostelman, Tsai Hong, Jeremy Marvel, "Performance Measurement of Mobile Manipulators", SPIE 2015, Baltimore, MD, April 2015.
7. ISO 9283:1998 Manipulating industrial robots - Performance criteria and related test methods.
8. ANSI/OPEI B71.9-2016 American National Standard for Multipurpose Off-Highway Utility Vehicles.