

STUDENT SUMMER INTERNSHIP TECHNICAL REPORT

Navigation and Positioning Tests for Vector Platform

DOE-FIU SCIENCE & TECHNOLOGY WORKFORCE DEVELOPMENT PROGRAM

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ABSTRACT

As part of the Hanford Mission, the Chief Technology Office (CTO) at Washington River Protection Solutions (WRPS) supports the maturation of technologies that increase safety and efficiency. Reducing personnel entrances into the Hanford site utilizing autonomous robotic platforms to carry out tasks, such as thermography for condition monitoring, decreases exposure risk as well as operational costs. WRPS CTO has thoroughly tested and observed the navigation and positioning capability of an autonomous robotic platform – the Waypoint Robotics™ (Waypoint) Vector – for over 40 hours for its application to this mission. From the results gathered in testing, the Waypoint Vector is recommended for use in tasks where the platform needs to arrive in a specific location but not rotate towards a specific target, such as general area monitoring and area-based sensing. The Vector can also be recommended for use in field tasks requiring a specific location but a loose tolerance in rotation towards a specific target, such as wide-angle camera image capture or thermal imaging with a pan-tilt device. However, the Vector cannot be recommended for use in tasks where an exact rotation towards a target is required, such as imaging with narrow field-of-view thermal and zoom cameras without a pan-tilt mechanism.

TABLE OF CONTENTS

ABSTRACT.....	iii
TABLE OF CONTENTS.....	v
LIST OF FIGURES	vi
LIST OF TABLES	vi
1. INTRODUCTION	1
2. EXECUTIVE SUMMARY	2
3. RESEARCH DESCRIPTION.....	3
3.1 Testing Location and Precautions.....	3
3.2 Description of Testing Method	5
3.3 Description of Test Session	5
3.4 Visual Aids for Imaging.....	5
3.5 Testing Preparation Checklist.....	8
3.6 Areas of Observation	9
3.7 Image Analysis.....	9
4. RESULTS AND ANALYSIS.....	12
4.1 Data.....	12
4.2 Discussion of Image Analysis.....	15
4.3 Observations from Testing.....	17
4.4 Maintenance Considerations.....	19
5. CONCLUSION.....	20
APPENDIX A.....	21
TEST SESSION NOTES AND OBSERVATIONS.....	21

LIST OF FIGURES

Figure 1: Overhead image of test location.....	4
Figure 2: Example of equipment setup.....	4
Figure 3: Model of visual aid.....	6
Figure 4: Mock image frames, from left to right: too far left, centered, too far right.....	6
Figure 5: Visual aid at 4 feet away from onboard camera.....	7
Figure 6: Visual aid at 6 feet away from onboard camera.....	7
Figure 7: Visual aid at 8 feet away from onboard camera.....	8
Figure 8: Vector on a pre-test cycle and tracks left in the gravel by solid tires.....	9
Figure 9: Comparison of two similar images from pre-testing.....	10
Figure 10: Example of an aligned image.....	12
Figure 11: Example of an in-tolerance image.....	13
Figure 12: Example of a missed image.....	13
Figure 13: Visual aid knocked over by wind during testing.....	16
Figure 14: Path planning variance evidenced by tire imprints in gravel.....	18
Figure 15: Path planning consistency evidenced by tire imprints in gravel.....	18

LIST OF TABLES

Table 1: Cumulative Testing Results Based on Image Comparisons.....	14
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1. INTRODUCTION

The Chief Technology Office (CTO) supports the Hanford Mission by researching, developing, and maturing technologies that increase safety and efficiency. As part of the CTO program, the organization works with both internal and external stakeholders. Mission Analysis Engineering is an internal stakeholder that maintains the condition monitoring group. The condition monitoring group have several key areas where an improvement in the workflow is desired, including a reduction of personnel entrances into the Hanford site to decrease exposure risk, overall reduction in error and variance in data gathered, as well as a reduction in operational costs. This scope of work includes condition monitoring, where staff enters the tank farms for several hours at a time to perform thermography of key components at the site. The time it takes to perform tasks such as thermography can be costly, and the time of the staff utilized can be better applied to other essential tasks within condition monitoring.

As such, it is attractive to develop an automated system that would allow for thermography to be carried out by an autonomous robotic platform, with minimal supervision and avoiding the requirement of having personnel physically present on-site to carry out the task. Additionally, the autonomous robotic platform would allow for more frequent monitoring of key components at the site, while providing a higher influx of data for a thermographer to analyze after each automated run.

The autonomous robotic platform that WRPS CTO is currently testing what applicable missions the Waypoint Robotics™ Vector can complete. This is a ready-to-deploy platform, and it has improved steadily over the past three years and now offers capabilities that are ready to be applied in tank farm field conditions, such as autonomous path planning and navigation. Historically, the Hanford site has used a variety of different robots to enhance overall workplace safety going all the way to B Reactor. However, the implementation of operator-less robotic platforms has not yet been fully realized.

In the case of the use of autonomous platforms for thermography, several concerns must be addressed to confidently assign the Waypoint Vector to the task of successfully analyzing a piece of equipment. For the thermography to take place, a thermal imaging device – such as a Forward Looking Infrared (FLIR) camera – must be brought out to the same location and a consistent image must be acquired. This image must record hot spots and areas of concern in essential equipment, such as pumps and electrical boxes.

It was important that the Waypoint Vector was tested to confirm and verify self-navigation capabilities to a target goal and orientation within normal operating conditions. These operating conditions – environmental factors such as high levels of heat and unpaved, undulating surfaces – can impact the viability of the autonomous robotic platform during highly repetitive tasks. The Waypoint Robotics™ Vector was modified by the manufacturer to operate in the conditions present at the Hanford site, which allowed the platform to overcome the aforementioned factors. The end goal for these tests was to have a solid basis to recommend the use of available robotic platforms based on the results of navigation and positioning precision testing over prolonged operation.

2. EXECUTIVE SUMMARY

This research work has been supported by the DOE-FIU Science & Technology Workforce Initiative, an innovative program developed by the US Department of Energy's Environmental Management (DOE-EM) and Florida International University's Applied Research Center (FIU-ARC). During the summer of 2020, a DOE Fellow intern Jeff Natividad spent 18 weeks doing a summer internship at Washington River Protection Solutions under the supervision and guidance of Technology Integration Project Manager Alexander Pappas. The intern's project was initiated on June 29, 2020 and continued through October 29, 2020 with the objective of testing and observing the navigation and positioning capability of an autonomous robotic platform – the Waypoint Robotics™ Vector – for its viability in use for Hanford tank farm tasks such as thermography for condition monitoring.

3. RESEARCH DESCRIPTION

Positioning is of great importance for thermography – it is desirable to have a platform that can reliably self-navigate to a designated location, orient itself towards a target in a precise manner and carry out the task of gathering thermal imaging data. As such, the navigation and positioning tests for the Vector platform are the focus of testing, which will verify and qualify the autonomous path planning and navigation capabilities of the Waypoint Vector. The initial phases of testing substituted using a thermal imaging device by using the embedded platform camera that is normally used for teleoperation and live monitoring of the Vector’s progress. This was done to accommodate for the lack of a direct interface between the Waypoint Vector and the FLIR® T530 camera provided by the Mission Analysis Engineering. The later stages of testing incorporated the FLIR® T530 after a physical interface was developed, enabling the use of the thermal camera with the onboard system.

The Waypoint Vector can perform its originally designated task of assisting in a warehouse workflow, but the changes in environmental conditions provided additional challenge. These challenges included complicating effects of heat and wheel slip on varying surfaces during prolonged operation of the platform. Several functions were affected, such as the odometry and localization capabilities of the platform, as well as overall endurance of the system during continuous use in a dynamic environment.

These tests are designed to help qualify the platform for use in the environment present at the Hanford site. By using a suitably similar surface type for the platform to navigate, we were able to observe the impacts of rough terrain and wheel slip in the overall odometry performance of the Vector through its path planning decisions and positioning at goal locations. The onboard camera was then used as an additional qualitative aid in determining the precision of the Vector in final positioning. Our concern for these verification tests primarily lie within the ability of the Vector to consistently and precisely position itself in designated locations and orientations.

The testing consisted of 40 hours of total operation, with test sessions in continuous blocks of at least 4 hours. The Waypoint Vector was monitored through visual operation and the onboard collection of visual data to catalog any major variances in stopping position and orientation. This was qualitatively verified through several visual aids including the image captured at teach target location, the observation of its final positioning during the testing cycle, and the consistency of paths taken to reach each target. Upon completion of the test sessions, the images captured with the onboard camera were compared to control images through both visual inspection and software processing. The successful completion of the data acquisition allowed for recommendation on whether the platform is suitable for supporting the Mission Analysis Engineering condition monitoring group.

3.1 Testing Location and Precautions

All test sessions took place on a small gravel patch located on the south side of the 2505 Garlick building, outlined in yellow in Figure 1 below. This small patch of gravel is used as a connection between two adjacent parking lots and as a spot for a dumpster which made it made it mostly

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ideal for the tests we conducted. The dumpster, a cone placed atop an access panel, and parked vehicles provide reference points for the Waypoint Vector to carry out localization. The gravel surface present is analogous to the surface that is commonly found inside the Hanford tank farms.

The precautions and considerations taken during test sessions at this location included enhancing robot visibility using a tall safety flag to alert transient traffic, as well as the setup of a small pop-up sunshade and safety materials used for environmental protection for workers. Additional considerations were made in where vehicles could be parked and equipment could be placed, outlined in red and blue respectively in Figure 1.

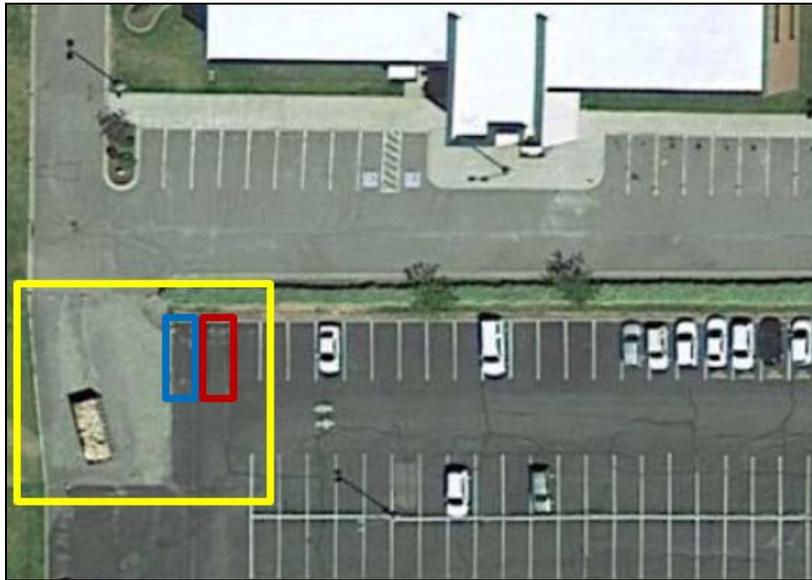


Figure 1: Overhead image of test location



Figure 2: Example of equipment setup

3.2 Description of Testing Method

Each test cycle was developed once the initial mapping was completed. Within the designated test area, three primary points were established for the Vector to self-navigate to and capture and image. The images captured at these points, referred to as *capture points*, are considered *primary data*. From prior testing and trials, it was observed that adding in additional *transition points* helped improve the ability of the platform to reach a set destination in a desired orientation. These transition points were placed between two points that the platform was anticipated to have difficulty navigating – such as when driving around the dumpster at the test location. Test sessions were conducted with transition points in use as well as not in use to highlight the impact of these points in the final positioning and orientation. At transition points, images are not captured by the Waypoint Vector, but observations were still made at these points. These observations, in conjunction with other documented occurrences during testing, are considered *secondary data*.

3.3 Description of Test Session

The 40 hours of testing was performed to ensure enough data was collected. Each day of testing is referred to as a *test session* which encompassed at least four hours of continuous testing. For the duration of a test session, only short stops were allowed for data retrieval and for the documentation of observations. The test sessions were broken down into multiple *test cycles*. Test cycles began when the navigation program was initiated on the Dispatcher software loaded on a computer connected to the wireless access point of the Vector. During a test cycle, the Waypoint Vector travelled along a loop and moved between each point up to a total of ten times. Each individual loop was referred to as a *test routine*. At the end of each test cycle – after several routines have been performed – the images were retrieved from the Dispatcher software and saved into folders separating specific test cycles within a session folder.

3.4 Visual Aids for Imaging

To ensure validity and quality of the observations and results gathered during a test session, standardized visual aids were used. The visual aids were meant to be uniform targets to be captured by the onboard camera at each capture point and served as orientation references for determining the final orientation of the Vector. A model of a visual aid used during testing is shown in Figure 3.

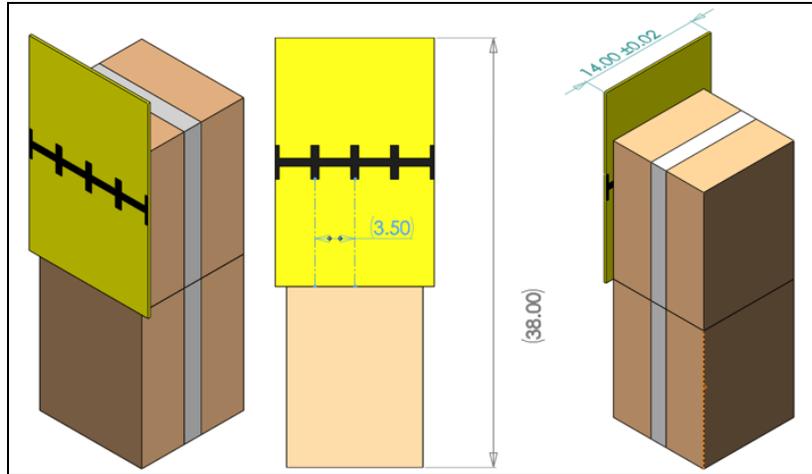


Figure 3: Model of visual aid

The visual aids each featured a poster board with uniform markings spaced out equally along the width of the board. By placing the visual aid either in the center or the edge of the image frame (an example of which is shown in Figure 4), the captured images could be compared to a control set of images – the first set of images in each test cycle. During the test sessions, the live feed revealed the offset of the robot from its stopping orientation, which was then validated during post-processing of the images.

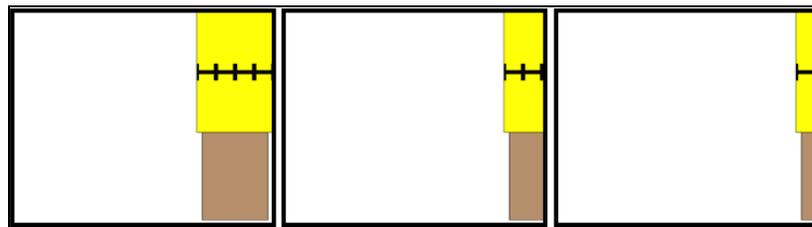


Figure 4: Mock image frames, from left to right: too far left, centered, too far right

For the test sessions conducted, the visual aids provided a clear indication of whether the Waypoint Vector was pointed correctly at the target or not, as well as provided an external reference that highlighted how the Vector was arriving at the target location. As an example, for most instances observed during testing, the Vector would stop in the same position each time, but the visual aid was not necessarily centered within the image frame when it came to a stop. This was useful in differentiating the overall navigation capability of the Vector (i.e. just driving from one point to another) versus the positioning capability of the Vector (i.e. being pointed in a specific direction at each point).

The visual aids were targeted at least approximately four feet from the onboard camera at the capture points during setup. This was to ensure that most of the measurement board is captured by the camera and that the markers could be clearly seen within the captured images. Additionally, if the platform moved closer to the visual aid than anticipated, the markers on the board were still visible within the image. Sample images of the visual aid are presented in Figures 5-7.

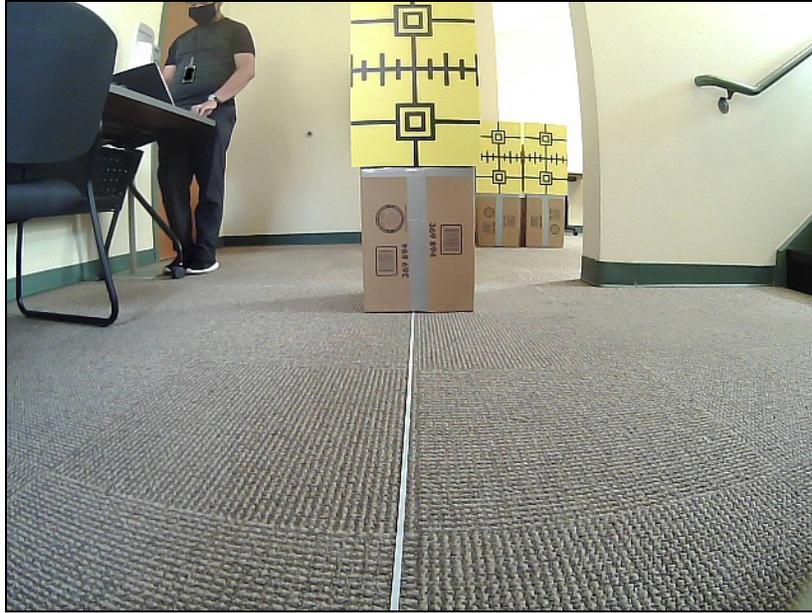


Figure 5: Visual aid at 4 feet away from onboard camera

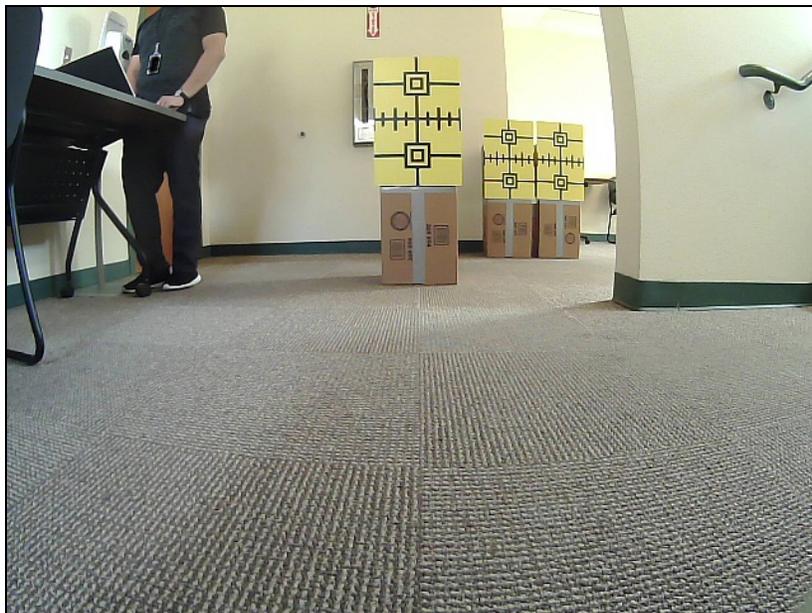


Figure 6: Visual aid at 6 feet away from onboard camera



Figure 7: Visual aid at 8 feet away from onboard camera

3.5 Testing Preparation Checklist

The following checks were utilized to ensure consistent testing. These minimized the transition time required if the Vector was not properly functioning at the beginning of the day, as well as provided general guidance for unsafe situations such as a high heat day or passing traffic.

Setup and Startup

- ✓ Power up the Vector, allow for startup procedure to finish, and perform a connection test to verify Dispatcher is functioning*
 - * If an electronic device cannot connect to Dispatcher, begin the recovery script and immediately resume the checklist after completion
 - * If recovery is required, the area must be remapped before continuing onto *Testing Duration* section
- ✓ Set up equipment in a suitable location near gravel
- ✓ Verify the position of static elements such as the dumpster and cone on the access panel
- ✓ Set up visual aids for camera capture in predetermined locations*
 - * To aid with the positioning of the visual aids, allow Vector to navigate to each of the image spots and align the visual aids using the live camera feed

During Testing

- ✓ Note any particularities in the Vector's path planning via visual observation of the tracks left in the gravel during testing
- ✓ Note any obvious differences in the Vector's stopping position, making sure to write which routine it occurred
- ✓ At the end of each test cycle, save all images from Dispatcher and clear them afterwards to ensure ease of organization
- ✓ Stay hydrated and cool off if necessary, using the facilities available and the vehicle

- ✓ Pause or halt any testing if the path of the Vector is deemed to be unsafe (for incoming traffic or for the platform itself)

Dismantling and Shutdown

- ✓ Disassemble all equipment at the end of each day (collapse sunshade/table/etc.)
- ✓ Make sure that all the images gathered are in fact accessible and organized into the session folders
- ✓ When powering down the platform, ensure that the charging cable is plugged in and seated properly
- ✓ Stow all equipment behind the Vector

3.6 Areas of Observation

Several key areas within the secondary data were considered to assist in confidently making the recommendation of the Waypoint Vector for supporting the Mission Analysis Engineering condition monitoring group. The first component of the secondary data was the overall path planning capability of the platform. As formerly stated, transition points were applied in some of the test sessions to assist the Vector in traveling from capture point to capture point and to improve final orientation. Between both types of points, the Vector could self-navigate and perform its own path planning to arrive at each point.

To observe the overall path planning of the Waypoint Vector, tracks left by the solid tires in the gravel were visually inspected and documented. To illustrate this, Figure 8 depicts the observable path imprint in the gravel caused by the Vector traversing the same location repeatedly over time. The Vector was documented to be consistent in path planning if the tracks in the gravel aligned well, while varied tracks in the gravel represented behavioral changes in path planning from point-to-point. A gravel rake was used to smooth over the imprints at the capture points after each test cycle.



Figure 8: Vector on a pre-test cycle and tracks left in the gravel by solid tires

3.7 Image Analysis

The recommendation of the Vector will come from the consistency of the data gathered – points of interest such as path convergence over an entire test session and initial observations of visual

aids within resulting images. There were no quantitative measures used in this report to verify end goal positioning. However, an additional visualization of precision was achieved through the comparison of images captured during test cycles to control images from the beginning of each cycle.

Utilizing image processing software – such as the OnlineImageDiff¹ comparison tool based on the ImageMagick[®] image processing suite – an assessment to the overall quality of the observations were made from the testing sessions. An example of an image comparison through the software can be viewed in Figure 9.

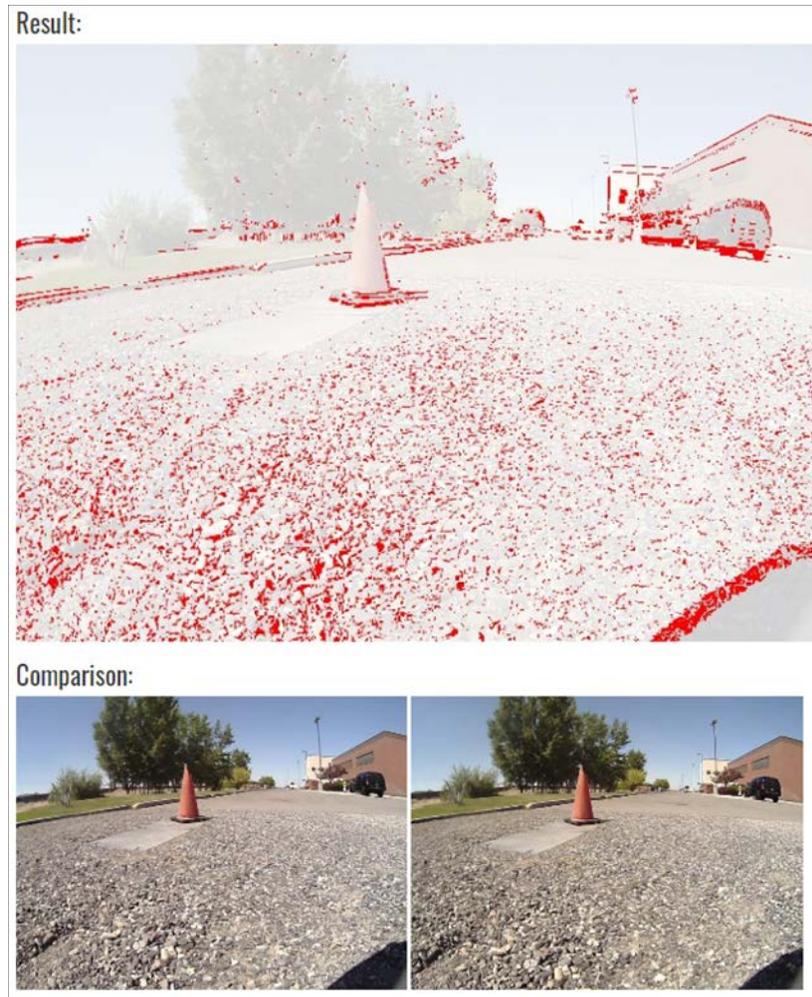


Figure 9: Comparison of two similar images from pre-testing

The notable aspects of utilizing image processing software to compare two images is observed by looking at the lower two images being compared in Figure 9. Through visual comparison alone, it is difficult to tell the difference between the two images. During the test sessions, these two images pass off as acceptable positioning of the robot. However, the accuracy of that

¹ From Online-Image-Comparison.com, © WaKi Software GmbH 2020

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statement cannot be guaranteed unless the testing observation is qualified with a different method. By processing images through the OnlineImageDiff software, the differences can be seen between the two images on a pixel-by-pixel basis that normally would not be evident from visual observation.

The top image in Figure 9 is an example of the software analysis of the lower two images. All the red dots represent anomalies the software picked up between the first and second image passed through. As presented in Figure 9, the images are different – albeit slightly – from each other. From these results we can determine the acceptable range of difference between two captured images – mid-cycle image and start-of-cycle image for example – and qualify the Vector’s precision in navigation. This image processing method is the most straightforward way to ensure quality of the results gathered throughout the test sessions.

4. RESULTS AND ANALYSIS

4.1 Data

The data presented in Table 1 encompasses over 40 hours of testing and provide an insight into the performance of the Waypoint Vector in navigation and positioning. This primary data numerically represents the number of aligned, in tolerance, and missed images that resulted from the comparison of a mid-cycle image to the start-of-cycle image. To illustrate the reliability of the Vector in positioning itself at a target location, a comparison is also provided between the number of acceptable images (number of aligned + number of in-tolerance) and the total number of images.

There are differences to be noted between how the three types of images presented in the table were assessed. For an image to be considered aligned, the resulting image comparison exhibited a near-match in the position of the visual aid within the image frame. An example of this would be when the comparison revealed that the visual aid markers aligned on top of each other. This is illustrated in Figure 10. Well aligned images were not a rare occurrence within the total results and represent the Vector's navigation and positioning capabilities under ideal circumstances.

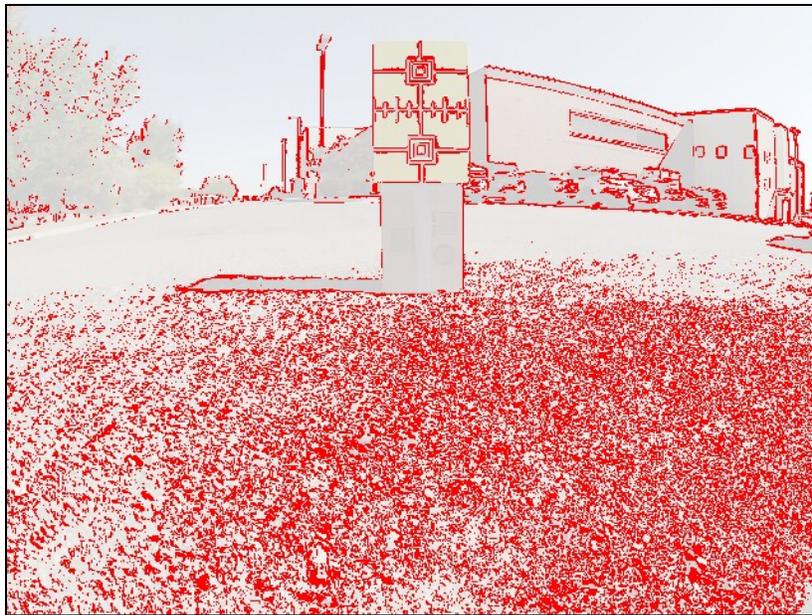


Figure 10: Example of an aligned image

An in-tolerance image represents cases where the resulting image comparison exhibited at most a two-marker variance observed from the uniform markings on the visual aid. For example, an image is in-tolerance if the comparison revealed that the visual aid shifted two markers to the right in a mid-cycle image, which is illustrated in Figure 11. In-tolerance images represent the bulk of the images gathered from the Vector's onboard camera and provide insight into the normal operation of the Vector.



Figure 11: Example of an in-tolerance image

A missed image is represented by a case where the visual aid was out of tolerance within the image frame – more than two markers right or left of the control image – or where the Vector captured an image that did not match at all, as illustrated in Figure 12. Missed images are the types of images that are preferably avoided. However, these images can be a result of external factors such as transient traffic and the maintenance status of the Vector.

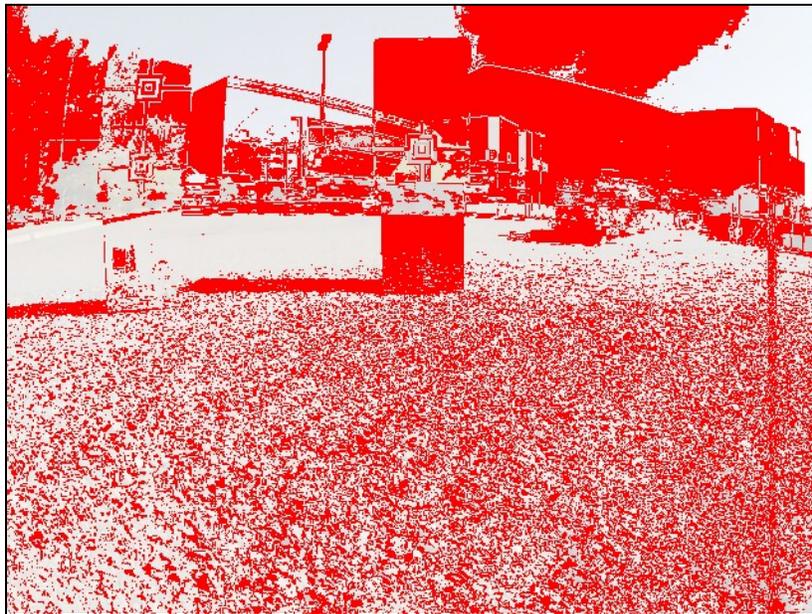


Figure 12: Example of a missed image

In Table 1, it is important to note the final six capture point sets with an asterisk. These final data sets represent test sessions held *without the use of transition points*. This was done to observe the effects of decreased guidance between capture points on the target positioning precision. Due to

the test cycles themselves being shorter, a slightly larger volume of data was able to be gathered in the same amount of time throughout the final test sessions.

The percentages in Table 1 were calculated by using the following and were performed separately for transition-in-use, transition-not-in-use, and combined:

$$\frac{\text{Total number of acceptable images}}{\text{Total number of images}} \times 100\%$$

Table 1: Cumulative Testing Results Based on Image Comparisons

<i>Test Session / Capture Point</i>	<i># Aligned</i>	<i># In Tolerance</i>	<i># Missed</i>	<i># Acceptable / # Total</i>
08-03-2020 / Point A	2	11	3	13 / 16
08-03-2020 / Point B	4	11	1	15 / 16
08-03-2020 / Point C	4	5	7	9 / 16
08-04-2020 / Point A	10	23	22	33 / 55
08-04-2020 / Point B	8	32	15	40 / 55
08-04-2020 / Point C	9	32	13	42 / 55
08-05-2020 / Point A	2	36	5	38 / 43
08-05-2020 / Point B	2	16	26	18 / 44
08-05-2020 / Point C	5	29	11	34 / 45
08-12-2020 / Point A	5	30	10	35 / 45
08-12-2020 / Point B	4	26	15	30 / 45
08-12-2020 / Point C	4	29	12	33 / 45
08-19-2020 / Point A	14	34	3	48 / 51
08-19-2020 / Point B	6	23	24	29 / 53
08-19-2020 / Point C	10	25	15	35 / 50
09-09-2020 / Point A*	7	19	37	26 / 63
09-09-2020 / Point B*	9	24	28	33 / 61
09-09-2020 / Point C*	3	22	38	25 / 63
09-21-2020 / Point A*	7	37	42	44 / 86
09-21-2020 / Point B*	7	46	33	53 / 86
09-21-2020 / Point C*	10	43	32	53 / 85
Totals	132	608	392	740 / 1132
Percentage Acceptable With Transition				73.54%
Percentage Acceptable Without Transition				52.70%
Percentage Acceptable Combined				65.37%

4.2 Discussion of Image Analysis

Table 1 presents positioning at the goal as well as the rotation, or yaw, towards the goal. The images gathered through testing are indicative of any clear misses of the image target (the visual aid), but alone do not represent the positioning of the Vector, only the orientation. Considering observations made throughout testing, conclusions can be drawn with respect to the Vector's consistency in both positioning and orientation, where the image analysis outlined the orientation capability while observations revealed the overall positioning capability. For the purposes of this discussion, the orientation refers solely to how the Vector is yawed towards the target – in other words, how well it has pointed itself towards the visual aid. The position refers solely to where the Vector stops, regardless of orientation, in comparison to designated target positions.

The total data is separated into three parts – percentage acceptable with transition points, without transition points, and the combined percentage. This highlights the impact on the initial setup of the testing routine, and ultimately the setup of the potential route the Vector may need to traverse on a large scale. As such, it is important to note that the test area chosen for the execution of the testing is significantly smaller than the potential area the platform may be operating in.

Results of Image Analysis

Image analysis alone clearly delineates the Vector's capability of orienting itself towards a target. From testing, it was observed that the orientation of the Waypoint Vector towards the visual aid was not always in an acceptable range. The combined acceptable percentage from Table 1 outlines this, which revealed that the Vector was correctly yawed towards the target 65.37% of the time. Although this value is not ideal, it is still an acceptable success rate for the Vector, which was modified from a production-ready unit to accommodate for environmental changes from the operation it was originally intended for in a warehouse environment.

The low numbers can reflect more than simply the Vector's orientation capability. Outside influences also affected some – but not all – of the images. Vehicles driving and parking near stopping points and the Vector itself impacted some of the captured images. During some test sessions, high winds were present that knocked down and shifted the visual aids from their positions and impacted some of the test images, such as in Figure 13. There are also considerations to be made when looking more closely at how the Vector behaved when transition points were in use versus how it performed when transition points were not in use.



Figure 13: Visual aid knocked over by wind during testing

Effect of Transition Points on Images Captured

As seen in Table 1, the percentage of acceptable images captured without the use of transition points reflected only 52.7% of the total number of images captured. However, the percentage of acceptable images captured with the use of transition points showed an improvement and reflected 73.54% of the total number of images captured. This is an improvement of at least 39%, which makes a case for the advantage of utilizing transition points to help guide the Vector along a route. This was calculated as follows:

$$\frac{\% \text{ acceptable with transition} - \% \text{ acceptable without transition}}{\% \text{ acceptable without transition}} \times 100\%$$

This improvement is attributable to the enhanced the path planning that the Vector carried out, which allowed the platform to more consistently plot an end to its path in a straight manner to arrive at the capture point. This improvement is desirable, especially for use cases where the Vector would be used for general remote visual monitoring where having a target in the exact center of the image frame is not necessitated. To illustrate this, the images captured from the onboard camera on the Vector are acceptable for evaluating large areas and respectively large changes within the environment it captures. Higher resolution cameras with wide-angle lenses would have comparably acceptable images and provide a clear picture of the desired area to be monitored.

However, this is not the case when the Vector is required to precisely orient itself towards a target and center it within an image frame; such as when equipped with a narrow-field-of-view thermal camera. An example of this is the FLIR T530 that was interfaced with the Vector at the conclusion of the navigation and positioning tests. Due to the use of narrow field-of-view lenses (anywhere from 24 to 14 degrees), it would be particularly difficult to center a desired target within its image frame using the Vector's positioning capabilities. This is particularly

emphasized if the Waypoint Vector is required to be close to the subject. The narrow field of view prevents a large scene to be captured up close, which creates a tunnel-vision effect. To capture a larger scene, the Vector would have to position itself further away from the target or employ wider field-of-view cameras.

4.3 Observations from Testing

Separate from the ending rotation of the Vector at each capture point, observations were made with respect to the platform's capability in arriving at the location requested on the Dispatcher software. Without considering the yaw, the Vector presents itself as advantageous for any task that may involve arriving at a general location autonomously. Throughout the multiple test sessions, many obstacles were introduced involuntarily to the test area – e.g., transient traffic, weather. Each time, the Vector arrived at the designated capture point or transition point with a stopping tolerance within a foot throughout each test cycle.

With the obstructions that were present during any given cycle considered, the platform was observed to successfully circumnavigate these obstructions and stopped in the same position every time. Provided with a task where the platform is simply needed to self-navigate to a general area, the Vector's behavior is highly acceptable and is indicative of the platform's general navigation capabilities even when exposed to a complex and changing environment.

Path Planning Observations

The first path planning observation made during testing is that the Waypoint Vector tended to take the straightest possible path from one point to the next. The platform did not consider if the next point it was driving to be a transition point or a capture point – to the Vector's computer, they are both the same. Within the Dispatcher software, waypoints can be set up that define both the location and the orientation the Vector must arrive at. The Vector does its best to adhere to the yaw instruction but appeared to prioritize arriving at the location. As such, the Vector introduced additional variances in its path planning to accommodate for the desired rotation at a waypoint, but this did not guarantee that it achieved the desired orientation.

Effect of Transition Points on Path Planning

The second observation made regarding path planning involved the impact of the use of transition points as part of the Vector's test routine. Without transition points, the path planning widely varies, likely due to the freedom the lack of transition points provided to choose paths to navigate around or near objects. An example of this is illustrated by Figure 14. On the other hand, using transition points assisted the Vector in consistently planning a path from one capture point to the next. This is likely due to the segmentation of the path into two sections, which makes its behavior more predictable, illustrated by Figure 15.



Figure 14: Path planning variance evidenced by tire imprints in gravel



Figure 15: Path planning consistency evidenced by tire imprints in gravel

In use cases where the Vector only needs to reach a general location or no small obstacles need to be expressly avoided, the use of transition points can be avoided. This simplifies the initial setup process and yields generally acceptable results. However, if there is a specific route desired or areas need to be avoided by the platform, transition points are highly recommended. The extra time needed for initial setup due to the inclusion of transition points is offset by more consistent path planning and improved positioning at the target location.

Recovery Behavior Observations

It is important to note the *recovery behavior* mentioned in the session observations located in the appendix. In some cases, the platform deemed the path ahead not clear or it deemed itself stuck

in the gravel. This happened in cases where it indeed is stuck or an obstruction is present, but it also happened as a result of outside influences such as passing traffic and weather. During a recovery behavior, the Vector stopped first then moved slowly in the opposite direction of the last direction traveled – slowly forward if it was backing up or slowly backward if it was travelling forward. The important aspect of the recovery behavior is that the collision avoidance system is completely disabled during this process. This means that the Vector may run into obstacles in its general vicinity.

There were instances that the Vector performed recovery behavior continuously – meaning one after another – which resulted in a collision with a visual aid or traversing out of the designated test area. However, observations indicated that these instances may have been influenced by poor waypoint setup or traffic being present in the area. An example of this were the final test sessions. The only difference between the two test sessions was the placement of one capture point and its visual aid, which was shifted slightly inwards towards the center of the test area. On the second to the last session, the location of the waypoint seemed to influence the continuous recovery behaviors seen at the end of the session, while these continuous behaviors were not present on the final test session. It is still useful to note that the omission of transition points in both sessions may have influenced these behaviors as well.

4.4 Maintenance Considerations

Prior to the final test sessions, a maintenance test was performed on the Vector. This included a partial disassembly to check the integrity of the internal connections and a thorough cleaning of the air curtain system as well as the LIDAR (Light Detection and Ranging sensor) lenses. Although this type of in-depth maintenance was done, it would not be considered part of what would be a routine maintenance schedule. The primary areas of concern for routine maintenance includes the air filters leading into the air curtain system and the cleaning of LIDAR lenses only. This basic maintenance should only need to be performed once a year, provided that the Vector was not exposed to severe conditions such as dust and rainstorms. The details of the maintenance procedures, including the in-depth breakdown of specific Vector subsystems, are detailed in a separate document serving as a maintenance guide for the Vector. While the platform was designed to operate with only a yearly inspection and maintenance, it is recommended that further operational testing is conducted to determine the actual maintenance needs of the platform.

5. CONCLUSION

The Waypoint Vector was tested and observed for over 40 hours. Throughout the test sessions, the Vector encountered the environmental conditions that are expected within the Hanford tank farms. This included high levels of heat, heavy wind conditions, and navigating complex and dynamic surroundings. From these test sessions, observations were electronically logged and organized alongside the images captured by the platform. Both the primary data (the images) and the secondary data (the observations) provided insight into the tendencies and behavior of the Vector under the aforementioned conditions.

From the results gathered in testing, it is recommended that the Waypoint Vector is used only in tasks where the platform does not need to orient itself towards a specific target. These types of tasks can vary widely but require the platform to simply arrive in the same location each time, regardless of the yaw orientation when it arrives at the determined locations. These tasks include being equipped with vibration sensors and the like, as well as scanning and imaging areas with a 360-degree or pan-tilt camera setup. In this case, the path planning assistance when performing the initial setup – the use of transition points – may be minimal or not needed, depending on the nature of the obstructions between different capture points.

The Vector can also be recommended for use in tasks where a specific location and orientation is required, but the yaw tolerance is relaxed. This recommendation is in place if transition points are used to help determine the path for the platform. These tasks, such as capturing images with a wide-angle camera for monitoring purposes or using a limited pan-tilt thermal imaging device, may not require an exact rotation of the platform with respect to the image target. Instead, they may simply require the platform to be pointed in a “ballpark” direction and be at a correct location. Taking the time to properly setup transition points in this case will help in the Vector’s final positioning significantly.

Lastly, the Waypoint Vector cannot be recommended for use in cases where an exact position and orientation are required. Examples of this use case can be depicted as mounting narrow field of view thermal cameras or zoom cameras for monitoring of targets without the ability to retrofit a pan-tilt mechanism. With the Waypoint Vector’s small yaw tolerance, more testing may be required on a larger testing area as the test conducted was not conclusive in determining the impact of the size of the traversed area on the final stopping orientation and location of the platform. It is possible that additional transition points could be helpful in guiding the platform to desired locations over a large area, however the accuracy of the platform’s final orientation on a large area cannot be guaranteed by the small-scale test area results presented in this report. Given the specific nature of these restrictions, tight yaw and location tolerances, use cases requiring this higher level of accuracy are unlikely.

APPENDIX A.

TEST SESSION NOTES AND OBSERVATIONS

August 3, 2020

Six test cycles conducted, with each cycle featuring five test routines. Test session began with mapping out the test area after a platform reset was performed the previous week to prepare the Vector for testing. Transition points were used between each capture point to help with path planning. Visual aids were placed within the image frame using the live feed from the onboard camera. Overall consistent behavior in path planning. Stopping tendencies include a right offset at the goal. Gravel imprints from the Vector's tires seem to affect the stopping position. Rake used to level stopping areas prior to conducting routines 4-6, minimal impact observed. Localization updates at each waypoint added to test cycle 5 – slight improvement in final positioning. Test stopped after cycle 6 due to the wind tipping the visual aids. Holes were added to the visual aids to allow for weight to be added for future testing.

August 4, 2020

Six test cycles conducted, with each cycle featuring up to ten test routines. Weight was added to each visual aid to help prevent tipping. Additional “start” waypoint added before point C – this can be considered a transition point. Gravel rake used to clear stopping areas prior to each test cycle. There are sections of deep gravel along the Vector's path, and these seem to affect the final positioning the most. Garbage truck entered the test area to pick up the dumpster on cycle 4, visual aid at point C had to be repositioned. Visual aid relocated to a new point to move path away from very deep gravel. On the 10th routine of cycle 4, personnel began dumping garbage into the dumpster – no major deviations due to this.

August 5, 2020

Eight test cycles attempted, with each cycle featuring up to ten test routines. Rake used to clear all stopping areas prior to each test cycle. Footprint padding setting was changed to 0.1 meters – this improved the path planning consistency slightly. Cycle 3, routine 6 a property management truck arrived and parked left of the dumpster and left before the end of routine 10. On cycle 5, the Vector drove into the visual aid at point C while performing a recovery behavior – this cycle is disregarded. On cycle 6, platform paused for some time at transition 1 and did not continue – cycle was cancelled but enough data was gathered to be used. Platform restarted prior to cycle 7 but began exhibiting strange behavior – platform skipped transition 3 and stopped executing cycle just after leaving point C. This cycle was cancelled but enough data was gathered to be used. Cycle 8, Vector stopped responding to Dispatcher navigation commands but can still be teleoperated using the Dispatcher keyboard control or the external controller.

August 12, 2020

Five test cycles attempted, with each cycle featuring up to ten test routines. No major path planning and behavior observations to be made with the Vector. However, weather had an impact on testing during this session. On cycle 3, the visual aid at point B tipped due to wind and was repositioned mid-cycle. During cycle 4, shifting and rotation of visual aids due to the winds was observed. Cycle 5, the robot pushed a visual aid at point B during a recovery procedure while the visual aid at point A tipped twice due to the wind – the visual aids were repositioned

mid-cycle. It is important to note that this may impact image consistency on a point-by-point basis.

August 19, 2020

Nine test cycles attempted, with each cycle featuring ten test routines. Observations were made before testing began including the dumpster being shifted slightly forward and the area near point B is muddy due to the presence of a puddle. Surprisingly the platform was not majorly affected by the muddy area. Strangely, the platform performed two additional routines on However, on cycle 6 the platform halted on routine 4. The Vector was restarted and returned to the starting position. Cycle 7, the platform once again halted on routine 4. It was suspected that the time of day might be affecting the sensor capture due to a specific angle of the sun.

September 9, 2020

Nine test cycles are conducted, with each cycle featuring ten test routines. This is the first session after the maintenance was performed on the Vector. This is one of the two test sessions where a simplified routine is implemented with no transition points. For the most part, Vector displayed consistent navigation with small hiccups in final positioning – this could be due to the lack of transition points to help guide the platform to the goals. It is important to note that there was a lot of foot traffic and some vehicle traffic in the area. During cycle 7, the Vector exhibited a wider variety of path planning choices. On cycle 8, the platform slowly reversed out of the mapped area at point C while performing continuous recovery behaviors. This behavior was replicated on cycle 9 but further into the routines.

September 21, 2020

Ten test cycles are conducted, with each cycle featuring ten test routines. This is the second session where the transitions are omitted from the waypoints. During the first cycle, there was a small collection error and resulted in only six routines being captured. The overall behavior was consistent. With the lack of transition points, any deviations leaving or arriving at capture points seem to affect the next positioning. During cycle 5, traffic drove through the test area. Cycle 6 there was a strange behavior exhibited where excessive recovery behaviors were performed by the Vector. Each cycle featured at least three recovery behaviors except for the first cycle.