Guideline for Automatic Guided Vehicle Calibration

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Abstract

This report documents the steps followed to calibrate an all-wheel steer Automatic Guided Vehicle (AGV) for optimal performance. Proper calibration of the steering and drive parameters of an AGV is critical for accurate dead-reckoning navigation, and improves the performance of an AGV servoing based on navigational information. Calibration of the navigation system alignment is also important for proper control of the AGV. This report discusses the calibration of the distance encoder, the steering offsets, and the sensor mounting angle on the AGV. Manual methods for performing the AGV calibration are discussed that require a minimum of specialized equipment.

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Introduction

Industry is making increasing use of robotics for material transport and processing. These robotic systems make use of many innovative sensing technologies and control techniques to improve their versatility [1]. The proper functioning of these transport systems relies on the accuracy and repeatability of the Automatic Guided Vehicle (AGV) used to move materials and equipment around the workspace. A key to obtaining the desired accuracy is proper calibration of the AGV.

A variety of different approaches to AGV navigation are discussed in the literature [1, 2]. Navigation approaches can be separated into two broad categories, those that perform dead reckoning and those that rely on external positioning references. Dead reckoning relies in a large part on accurate estimation of the distance and direction the AGV travels. Poor calibration of an AGV can lead to serious positioning errors. Small errors in the commanded steering and the measured distance accumulate to produce large positioning errors [3, 4]. For AGVs that rely on external navigation resources, the ability to accurately servo to a desired location can be affected by the quality of the vehicle's calibration.

This document describes the process of calibrating an all-wheel steer AGV. The National Institute of Standards and Technology (NIST) AGV, shown in Figure 1, has three independently driven and steerable wheels. The use of three wheels in a tricycle configuration is relatively common among AGVs [5, 6]. This configuration allows the AGV to be moved in a number of different ways. Ackerman steering refers to a motion

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similar to that of a front-wheel steered car. One or more of the AGV wheels are turned so that the vehicle travels in an arc around a turn pivot point. Crabbing refers to motions where all of the AGV wheels are turned together. Unlike Ackerman steering, this allows the AGV to move in any direction without rotating the body of the AGV. For these maneuvers to be carried out accurately, the relative rotations of the wheels and their relation to the navigation system need to be properly calibrated.

Figure 1: NIST AGV with onboard manipulator (background) moving to dock with a NIST reconfigurable mobile manipulator artifact (foreground).

However, current AGV steering calibration mainly includes locking the two rear steer wheels together at 0°, allowing only the front wheel 0° steering rotation to be adjusted, and then testing that the AGV moves along a straight line. Figure 2 shows this technique where the AGV has an onboard laser pointing along the travel direction and shining on a piece of paper taped to the wall. An initial laser spot position is marked on the paper. The vehicle is then moved approximately 10 m or more along a straight line and the laser spot position is again marked. Ideally, the laser spot does not move laterally when the vehicle moves demonstrating that the steer wheel is aligned with the fixed wheels. Up and down spot motions are due to floor undulations and are not relevant to the test. The test, unfortunately, does not include calibration of the rear steer wheels.
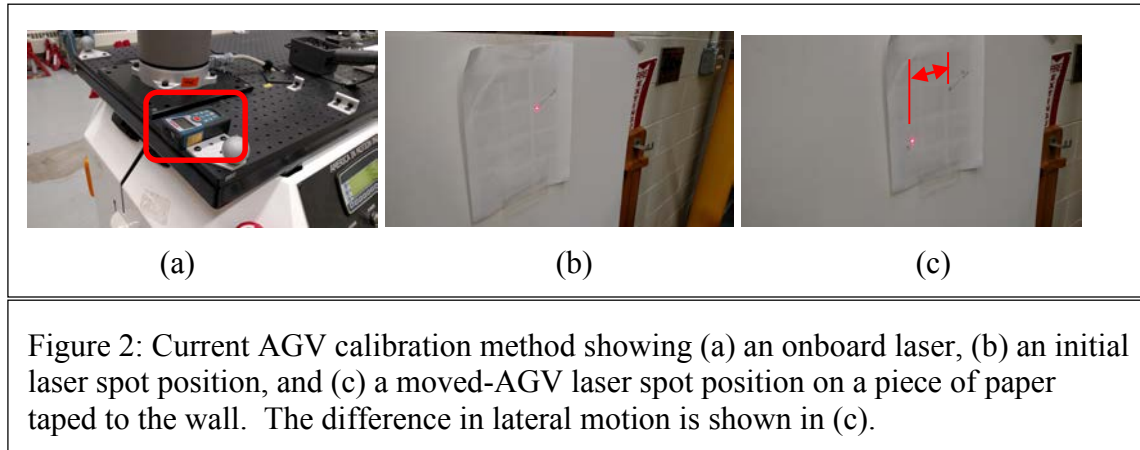
Figure 2: Current AGV calibration method showing (a) an onboard laser, (b) an initial laser spot position, and (c) a moved-AGV laser spot position on a piece of paper taped to the wall. The difference in lateral motion is shown in (c).

This document discusses the specific procedures used to calibrate the NIST AGV with all-wheel steer. The method for updating the parameters will be different on every vehicle, but the calibration procedures should have a wide applicability to a number of different vehicles. These procedures cover a number of steering, drive, and navigation sensor calibrations issues.

A number of observations led us to conclude that our AGV was out of calibration. High repeatability can often be achieved by always approaching a commanded stop location along the same path segment and from the same direction. Alignment of the AGV and the workstation can be achieved by moving the workstation to match the stop location of the AGV. In this situation, small errors in the vehicle tracking are not important, as long as they are repeatable. For our work with mobile manipulators, we wanted the AGV to be able to accurately stop at the commanded position, regardless of the approach direction or angle. We noted that there was a large deviation between the commanded stop point and the actual stop point, as reported by the vehicle's own navigation system. The AGV was consistently pulling to the left of the direction of travel and stopping short of the desired point by several centimeters. Errors as great as approximately ± 25 mm were measured between stopping points when the AGV was driven to the same coordinates from opposite directions. This is not reasonable when the navigation system can repeatably measure the position down to 4 mm.

While there are a number of papers on methods for automating the calibration of vehicle servo parameters [4, 6, 7, 8, 9], we chose to do a strictly manual calibration of our vehicle. The main reason for discussing manual calibration methods is the minimal equipment required for taking the measurements. Some automated calibration procedures discussed in the literature require specific sensors to be available on the AGV, as well as access to the sensor interfaces. These are not always available on a particular AGV. Others require expensive external ground truth sensor systems to measure the movement of the AGV. Also, there are calibration issues that are not directly observable from the motion of the vehicle, such as the toe-in of the wheels.

Calibration Procedures

The following calibration procedures were performed on the NIST AGV in order to improve its ability to repeatedly move to a commanded point from different directions. The calibrations also improved the ability of the AGV to accurately track a commanded path. A number of parameters will need to be read from the AGV controller, and some will have to be modified, in order to perform the calibrations described in this document. The specifics of reading and modifying the AGV parameters will be vehicle specific, and the operator will need to refer to the AGV's technical documentation for the specific names of the parameters and the methods required to access them.

Steering Encoder Offsets

Our AGV has three drive wheels, each of which can be independently steered. Each wheel has a steering encoder offset that defines where 0° turn is located. If the wheels are not properly aligned, the vehicle will tend to turn left or right when commanded to drive straight ahead. This affects the vehicle's ability to servo to the commanded path. Typically steering is controlled using a PID (position, integral, differential) controller. The error is measured as deviation from the desired path. When driving along a straight path, the steering error will increase until the proportional correction offsets the steering offset error, causing the vehicle to track off to the side of the desired path by some amount. The wheels on the NIST AGV are arranged in a tricycle pattern, with two wheels in the rear and a single wheel at the front; however, these procedures apply to four wheeled vehicles as well.

Wheel toe-in

Toe-in is the alignment of paired wheels. On the NIST AGV, since it has a tricycle arrangement of wheels, this only applies to the rear wheels. On a vehicle with four wheels, the toe-in of the front and rear pairs of wheels needs to be adjusted. Ideally the wheels should be parallel to each other, a toe-in of 0°. We corrected the toe-in on rear wheels by physically measuring their alignment. This was done by laying a ruler along the sides of the wheels as shown in Figure 3, drawing the lines on a piece of paper, and then measuring the divergence/convergence of the lines. The total angle was computed, and half that angle was added/subtracted from the right/left wheel rotation parameter. The absolute alignment of the wheels with the AGV chassis is dealt with in a later calibration step. The angle needs to be scaled into encoder counts and added or subtracted from the appropriate steering encoder offset. The relationship between encoder ticks and steering angle is determined by the gearing ratio and the number of encoder ticks per revolution of the steering mechanism. This information should be available in the AGV's technical documentation.
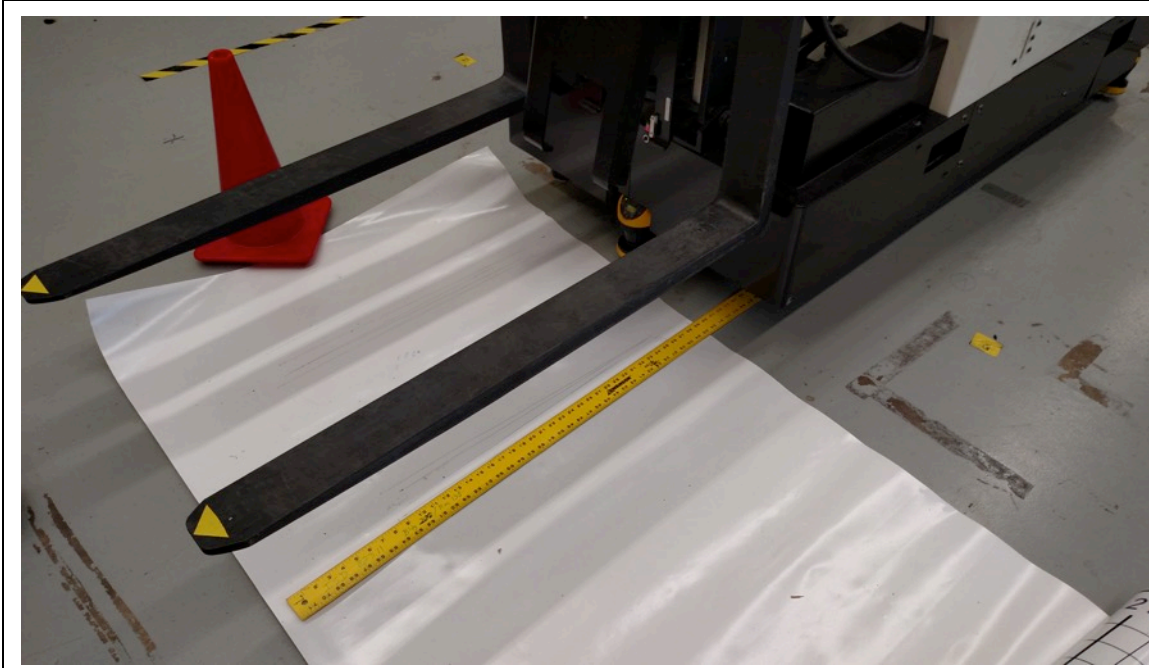
Figure 3: Marking out toe-in angle on a sheet of paper.

The toe-in angle can be computed as,

$$\theta = \tan^{-1} \frac{(d_2 - d_1)}{L},$$ (1)

where d_1 and d_2 are perpendicular distances from one line to the other, and L is the distance between the perpendiculars.

Tracking a straight line

The next step in calibrating the steering encoder offsets is to get the vehicle to track straight. The current straight-line steer measurement technique is discussed in the Introduction and is expanded here. If the front wheel(s) are not parallel with the rear wheels, the AGV will drive along an arc when commanded to drive straight. In order to perform this test, all AGV wheels are set to their 0° position and the vehicle is rolled forward and back between two positions on the floor. Refer to the technical documentation for the AGV to determine how to perform this operation. The front wheel encoder offset is then adjusted until the AGV tracks a straight line with the rear wheels locked. If the AGV is turning to the right, the encoder offset value should be increased. A discussion on the calibration of a three wheeled robot is given in [5].

The curvature of the vehicle path was observed with respect to a straight line while manually moving the vehicle forward and backward with the steering locked at 0°. First the AGV is moved forward and back to establish the endpoints of the path. A straight line visual reference is created by stretching a flexible tape measure taut on the ground between the start and end points of the path. The deviation from the straight path is observed visually. The tape is shown stretched across the floor with the AGV at one end of the path in Figure 4(a). In Figure 4(b) the AGV is shown at the mid-point of the path and has

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deviated from the straight line. The steering offsets can be adjusted incrementally until the AGV drives straight, or the steering correction can be calculated from the length and deviation of the path. In either case, the correction should be applied to both the front and rear wheels, simultaneously. Half of the correction is added to the front steering offset and half is subtracted from the rear wheel steering offsets.

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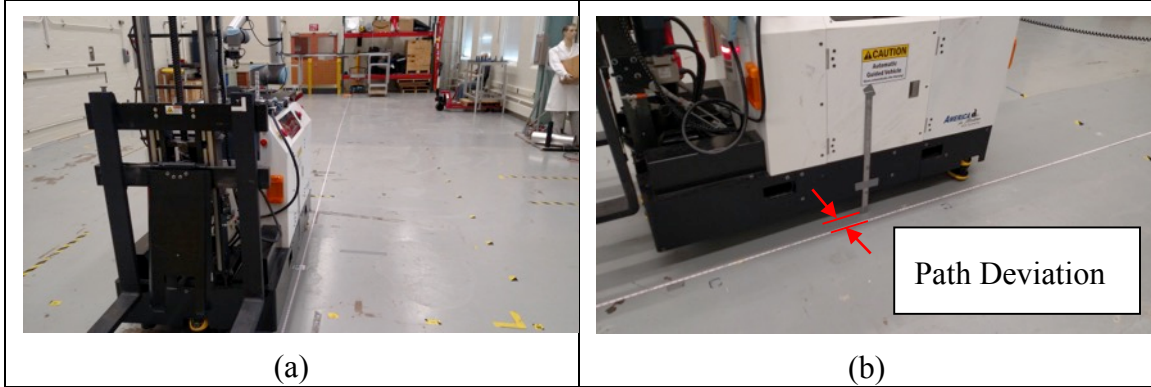<tr><td>(a)</td><td>(b)</td></tr>
</table>

Figure 4: Path deviation is measured relative to a tape measure stretched between start and end points marked on the floor (a) AGV at start point (b) AGV at mid-point showing deviation from straight path.

Using the intersecting chords theorem, the radius of curvature of the vehicle path can be computed as,

$$R = \frac{4d^2 + L^2}{8d}, \tag{2}$$

where d is the offset from the straight line path, and L is the length of the straight line path. Then the steering offset can be computed as,

$$\theta \approx \tan^{-1}\frac{w}{R}, \tag{3}$$

where w is the distance between the front and rear wheels. The value of R needs to be adjusted up or down based on how far the reference point (our ruler) is from the centerline of the vehicle.

Correct crabbing

Crabbing describes the AGV body orientation remaining constant while the AGV steers, for example, keeping the body straight while moving diagonally rather than straight ahead. The undesirable crabbing is corrected by moving the AGV back and forth past a fixed reference point (in our case the corner of a table) and measuring the clearance distance as the front then the back pass this fixed point. This is done in manual mode with the wheels locked at their 0° position. The difference in the measurements and the base line are used to compute an angle correction. The angle correction is then added to all three wheels. The corrections are done in unison to preserve the steering alignment done in the previous step. At this point, the AGV should be driving straight, with no crabbing.

Figure 5 shows the measurements being made from a stationary reference point (the corner of a stationary table) to the vehicle as it is driven past along a straight line. The measurements are made to a feature on the vehicle that is parallel with the centerline of the

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AGV. In this case, it is the edge of a mounting plate on the top of the vehicle. In Figure 5(a), the distance is measured as the front of the AGV moves past the corner. In Figure 5(b), the distance is measured at the trailing end of the plate.
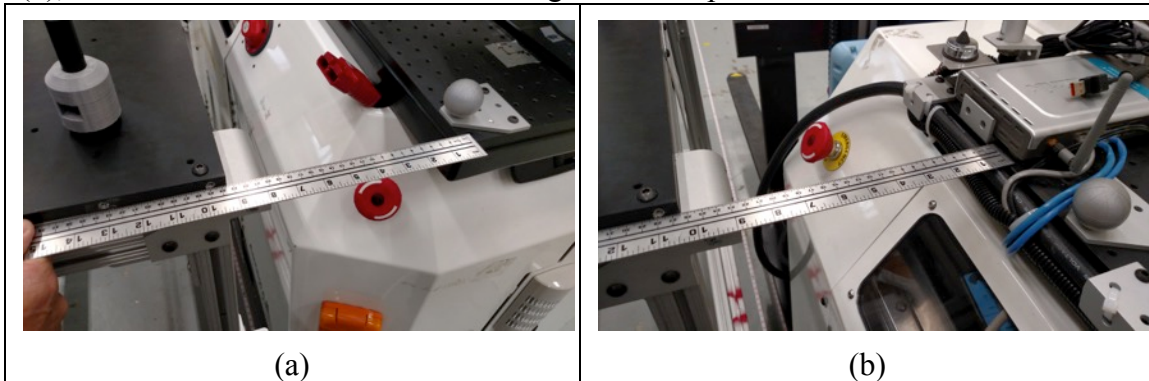

| (a) | (b) |

Figure 5: Crabbing is measured as the AGV moves passed a fixed reference point (a) measuring from front of vehicle to corner of table (b) measuring from back of vehicle to table corner.

The offset angle can be computed as,

$$\theta = \tan^{-1}\frac{(d_2-d_1)}{L},\tag{4}$$

where d_1 and d_2 are the distances between the stationary reference point and the vehicle, and L is the distance between the points along the length of the vehicle.

Adjusting lateral error

When stopping at a commanded point, it was observed that the vehicle was stopping consistently to one side of the point relative to the direction of travel. Since the vehicle was tracking straight with the wheels locked at their 0° position in manual mode, it was deduced that the problem lay in the alignment of the navigation sensor with what the AGV considered straight ahead. Under servo control this misalignment would cause a consistent pull to one side or the other until the PID controller built up enough position error to compensate for the misalignment.

The sensor position on our AGV relative to the vehicle coordinate frame origin is given by four parameters:

- ScannerX – The distance of the sensor mount point from the vehicle origin along the lateral axis of the vehicle.

- ScannerY – The distance of the sensor mount point from the vehicle origin to the left of the lateral axis.

- ScannerZ – The vertical distance of the sensor mount point above the vehicle origin.

- ScannerAngle – The angle between the vehicle axis and the sensor axis in degrees.

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Of these, the ScannerAngle is the only one we are concerned with. It compensates for the mounting alignment of the sensor relative to the vehicle centerline. The navigation sensor used on the NIST AGV derives the position of the vehicle by measuring the distance and angle to a collection of fixed reflective markers placed about the vehicle workspace. This data is processed and filtered to produce the two-dimensional (2D) position and orientation of the vehicle in real time. The navigation sensor mounting angle, ScannerAngle, was adjusted until the lateral error at the path points was reduced to an acceptable value. Refer to the technical documentation for the vehicle being calibrated to determine how to adjust the offset for the scanner mounting angle.

This corrected the lateral error that was occurring during autonomous motions by more than an order of magnitude. At this point the AGV, driving a straight line, had a much reduced lateral positioning error.

Wheel Encoder Scale

Each of the wheels has an independent distance encoder scale parameter that is used to translate revolutions of the wheel to distance traveled. Over time, the diameter of the wheel will change slightly with wear, and even when new, the diameter of the wheel is not known with a great degree of precision. Changes in the diameter of the wheel will cause the AGV to travel different distances per revolution of the wheel. Precision control of the vehicle stopping relies on an accurate mapping between wheel motion and distance traveled.

To adjust the wheel encoder scale, the AGV is driven along a straight line and the distance traveled is measured. The distance traveled, as reported by the control system for each wheel, is compared to the actual distance traveled. The current wheel encoder scale setting is observed, and a correction is computed. The equation for computing the new scale is:

$$S_1 = \frac{D_e \, S_0}{D_a}, \tag{5}$$

where S_1 is the new encoder scale, S_0 is the initial encoder scale, D_e is the encoder distance, and D_a is the actual measured distance. The value of the encoder scale is typically expressed in distance traveled per encoder tick. The reported encoder distance D_e needs to be read from the AGV controller. There will typically be an individual encoder scale parameter and drive encoder distance value for each of the wheels. The encoder distance D_e is determined by noting the drive encoder distance at the start and end of the move and taking their difference.

In our case, the measurements were taken by commanding the AGV to move between two positions located along a straight path using the AGV's control system. The drive encoder distance was recorded at the start and end points to compute D_e. The actual distance was measured by marking the start and end positions on the floor and measuring with a measuring tape as shown in Figure 6. To provide an accurate mark for the start and end positions, a ruler was taped to the side of the AGV to allow that point on the vehicle to be accurately transferred to the ground plane.
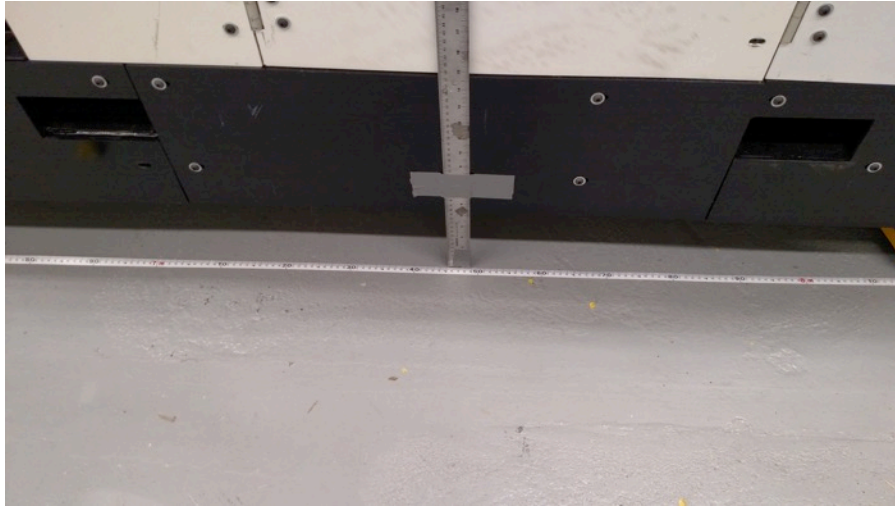
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Figure 6: Actual distance traveled is measured using a tape measure on the floor with ruler used as a reference point on the vehicle.

Stopping Tolerance

At this point the AGV was still stopping short of the commanded point by a distance that was significantly larger than the corrected side-to-side positioning error. We examined the technical documentation of our AGV for a discussion of the parameters that affect how the AGV decelerates and stops when it approaches a commanded stop. From this description it was determined that the parameter that needed to be adjusted to correct the stopping error was the StopTolerance. This parameter specifies the distance from the goal where the final deceleration to the stop point begins. The deceleration starts from a fixed 'creep' velocity used during the final approach to the goal point. The distance traveled during the deceleration interval will be nominally constant but unknown. The stop tolerance is adjusted to match this deceleration distance.

A three-point path was configured along a straight line. The vehicle was programmed to stop at the center point coming from both directions. The locations where the AGV stopped were marked on the floor. The distance between the marks was measured, and half of this distance was added to the StopTolerance, since the AGV was stopping short of its goal. If the AGV overshot the goal, half the distance would be subtracted from the StopTolerance instead. This correction improved the NIST AGV's stopping accuracy by more than an order of magnitude.

Observations

Calibration of the AGV's control parameters is critical to optimal performance of the vehicle. For vehicles that rely on dead reckoning to determine their position, small errors in steering and odometry can accumulate quickly over time and adversely affect the navigation of the AGV. For AGVs that make use of external navigational aids, proper calibration of the vehicle is needed for accurate servoing to meet navigation goals.

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Automated calibration is an interesting research topic, and can be a great labor saver when a large number of identical vehicles need to be calibrated. However, automated calibration systems rely on the availability of specific sensing systems on or off of the AGV. For the small manufacturing system, reliance on specific, and often expensive, sensor systems for calibration of the AGV is not always practical. This report has used a minimalistic manual approach to adjusting the necessary AGV parameters.

The order of the calibration steps listed reflects the order in which we recommend the adjustments be made. The order in which we actually performed the steps was slightly different than the order presented in this report. The order in which the calibration steps were performed was the result of systematically trying to eliminate various flaws in the motion of the vehicle, and was not specifically planned out ahead of time.

In this ordering, alignments relying on strictly physical measurements are done first, followed by alignments done while moving the AGV in manual mode with the wheel position locked, followed by tests where the vehicle is being moved between points under servo control. The wheel alignment steps were also reordered to reduce possible inaccuracies in the later calibration steps.

The specific calibration procedures described here were tailored to our specific AGV's needs. However, most of the procedures described in this report apply to a large class of similar AGVs being used in industry. The calibration of the NIST AGV resulted in a significant improvement in the vehicle's performance.

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