Redundant Control Method for Automated Guided Vehicles

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ABSTRACT

The purpose of this research is to explore the current state of automated guided vehicles (AGVs), sensors available for the vehicles to be equipped with, control systems for the vehicles to run on, and wireless technology to connect the whole system together. With a technological push towards increasing automation and maximizing the possible throughput of systems, automated technology needs to improve for trackless and wireless systems such as vehicles that can be used to move loads in a vast array of applications.

The goal of this research is to develop and propose improvements in both vehicle and control system design that allows for improved safety and efficiency. Right now, the main issues are maneuverability of vehicles and control systems being adaptive enough to deal with connection issues between systems. While prolonged connection issues will result in a stoppage of operation of any system that relies on wireless communication, intermittent issues can also cause systems to have an emergency stop. I have looked into ways to offload tasks from the central system and allow the vehicles themselves to have more computational privileges such that they can operate in a semi-independent manner.

The result is a proposed system that remedies or limits negative effects that currently cause issues with trackless vehicles and control systems working with remote systems that communicate via wireless means.

Keywords

Automated Guided Vehicle, Hybrid Controller, Redundancy, Sensors, Trackless Vehicle.

1. INTRODUCTION

Automated guided vehicles began simply as a vehicle following a radio signal emitted from a wire on the ground. This has advanced to the point where we are very close to passenger vehicles being able to drive themselves on a widespread level. Vehicles are used in a wide variety of applications from personal transportation, to carrying payloads, to entertainment purposes. Industrial applications for autonomous trackless vehicles are tough because the vehicles have to be able to operate in a very dynamic and hectic environment that doesn't have the benefit of infrastructure and ruleset that autonomous vehicles on a road are able to use. The fact that the applications can have the vehicles operating either indoors or outdoors or even moving between the two creates tracking challenges for the system.

Controllers that operate autonomous vehicles must either be contained fully on the vehicle, as with self-driving cars, or can be centrally located and connect wireless to a plurality of vehicles. While trackless vehicles that connect to a wireless control system still need to have on-board computing capability to process the signals they get from the central controller, they are usually tethered to the signal and rely on having a stable connection. There must be ways to improve the balance of computing capability between autonomous systems that rely on a central control system that allow for more forgiving operation in situations where signal interference is possible.

2. AUTOMATED GUIDED VEHICLES

Typical AGVs tend to be of a simplistic design and control due to their autonomous nature. Keeping the vehicle and controller simple limits the chance that there is something that can go wrong for these potentially huge machines that are moving around without much human oversight. In general, AGVs consist of platforms that have one or two drive wheels with the rest being free-moving castor wheels to carry weight and provide balance.

2.1 Steering

Steering is one of the most important factors in the AGV because the method of steering influences the mobility and control of the platform. There are three majors steering schemes used on AGVs.

The most basic steering control is from a differential drive wheel configuration. This is when there are two drive wheels that are parallel to one another and the turning process is created when there is a difference in wheel speeds. This is similar to how a tank steers. It benefits from its design simplicity but is unable to perform more complex movements.

Another steering method is a three-wheel steer drive configuration. There are two castor wheels and the one powered drive wheel that can also spin to control direction. This is the type of steering that is available on most forklifts. This method is more maneuverable than differential steering and can perform smooth and accurate motions but still isn't the most maneuverable option.

The third option is a two steer-drive wheel configuration. This configuration has two drive wheels that can be rotated and two castor wheels. This steering configuration allows from the vehicle to move in any direction and turn on the spot. Similar to the 2 steer-drive wheel configuration is the Quad wheel configuration. This combines two fully rotatable drive wheels with two castor wheels to give the best range of motion and highest maneuverability [37].

A possible improvement that will be explored is having four drive motors that can all be rotated independently. This has the advantage over the two steer-drive configurations in that all four wheels are driven, allowing for double the available power and can also allow for power efficiency and reliability by disengaging a pair of wheels to drop the power consumption by half or allow for continued operation if a motor for a wheel breaks or a sensor malfunctions. This fault-tolerance system will allow for increased efficiency and reliability.

2.2 Vehicle Design

A more robust control system for an AGV requires a more robust vehicle. The design of this vehicle allows for size scalability and maneuverability for a wide array of uses. The vehicle has a very simple design consisting of 3 main parts.

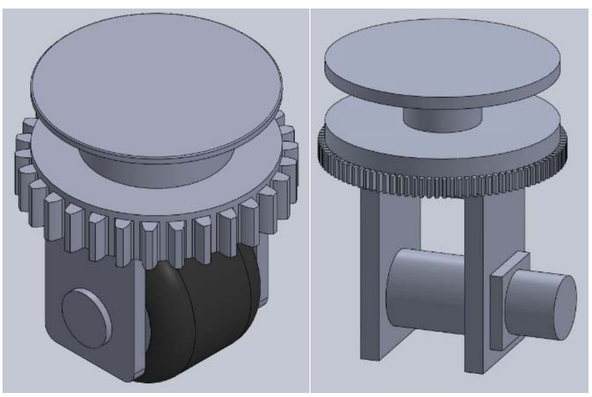

Figure 1. Wheel mounting bracket showing rotational gear interface and space for linear motor mounting

First is the wheel and mounting bracket. This consists of the wheel, the bracket that the wheel is mounted to, and the drive motor for the wheel. Since the wheels are meant to spin a full 360 degrees the bracket must be able to easily rotate with respect to the main platform while also being able to stably support the loading of the vehicle. To account for both these needs, the cuff of the bracket has a wide plate on the top and bottom that help distribute the loading for each wheel assembly while also limiting the frictional forces that need to be overcome for rotation of the cuff to be performed. Figure 1 shows an earlier design of the wheel and cuff. As can be seen midway up the bracket, there is a gear built into it. This is for the second motor to interface with to control the wheel orientation. In figure 1 the placement of the drive motor is shown on the outside of the bracket lined up with the axis of the wheel. The bracket can either have one motor mounted to one of the sides, or two motors working in tandem mounted on both sides to amplify the power available to the wheels while keeping the size of the motors in check.

Second is the lower platform. This is the main housing for the vehicle as it is where the wheel brackets link into as well as housing the required mechanics for the vehicle such as power source (batteries or generator), the motors that control wheel orientation, most of the onboard sensors, and the computer system.

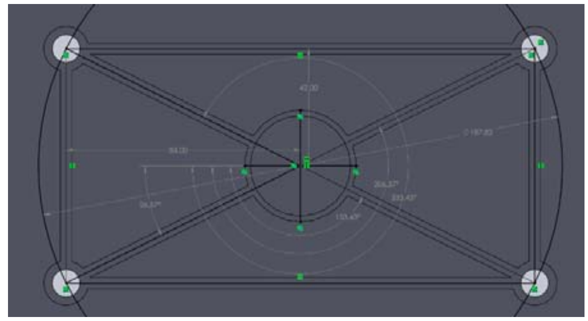

Figure 2. Underside of platform showing a possible wheel configuration with respect to the center of the vehicle

To make control of the wheels as simple as possible, they are laid out along a circular pattern with respect to the center of the vehicle. By having the wheels laid out in a circular pattern about the center of the vehicle, it creates an easy reference not only between the central point of the vehicle, where the position will be taken from, but also an easy reference between wheels so that rotational maneuvers have the most evenly distributed output requirements. This layout allows for the required wheel velocities and orientations to be easily calculated getting eight outputs (velocity and orientation of each wheel) from three desired inputs (liner velocity, direction, and vehicle orientation). Knowing only the length and width of the wheelbase, the location of all four wheels can be resolved for the system to properly calculate the required motor outputs to the wheels.

Since each wheel is independently controller that mean each wheel has two motors, one each for linear and rotational velocity outputs. Each wheel system is connected to the main platform via a cuff that is designed to be able to carry the required loadings for the vehicles desired application. The rotational motor is mounted within the platform and interfaces with the wheel system via a gear. The tricky part comes with the mounting location of the drive motor. There are two options, on the platform or directly to the wheel mounting bracket. Mounting from the platform would require a driveshaft that can not only operate at an angle, but be able to compensate for the rotational movements with the vehicle without affecting wheel velocity. Mounting from the wheel bracket gives an easy, direct connection to the wheel but creates an issue with wiring back to the platform to be able to receive power and a signal. Mounting to the wheel bracket was determined to be preferable since slide contacts can be used for the transfer of power and required data.

Figure 3 shows how given a desired linear (red arrow) and rotational (blue arrow) velocity for the vehicle as a whole, it can be broken down to the wheel components which combine for the total output for each wheel (green arrow). Notice how the blue arrows for each wheel are always tangent to the circle that the wheels all lie on. The resultant motion shown is of the vehicle driving in a straight line while its orientation is rotating counter-clockwise.

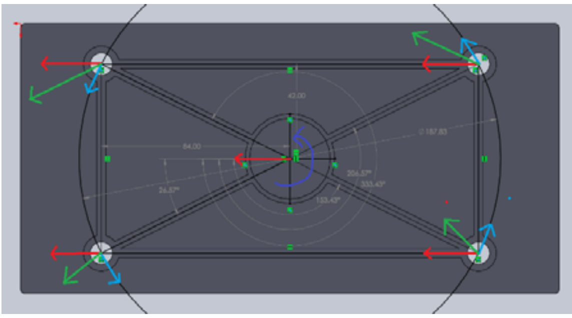

Figure 3. Desired linear and rotational velocity depicted in the center result in the wheel outputs (green, with red (linear) and blue (rotational) components

Figure 4 shows a design for the lower platform where there are large recessed areas for the wheel bracket to slot into along with ribbing along the platform to reinforce it in areas where forces are expected to be transferred along the body of the vehicle. The positional sensors can also be seen mounted at each of the corners of the vehicle. Having a sensor on each corner allows for an environmental sensor to be able to see at least two of the vehicle sensors at a time assuming no other obstacles possibly blocking the line of sight besides the cargo onboard. Figure 5 shows the same lower platform with the wheels in place. The top of the bracket cuff is flush with the platform ribbing and the built-in gear are exposed below the platform. This allows for the orientation motors to be mounted to the lower platform and have them connect to the wheel brackets via a hole in the floor of the platform.

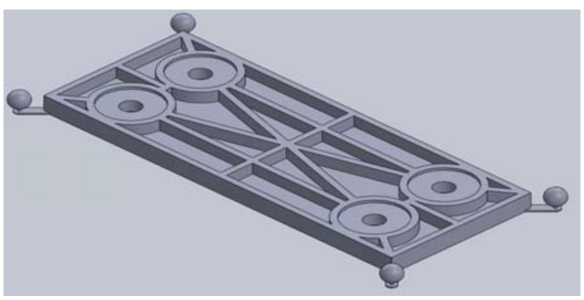

Figure 4. Lower platform complete with cutouts for wheel brackets and positional sensors mounted to corners

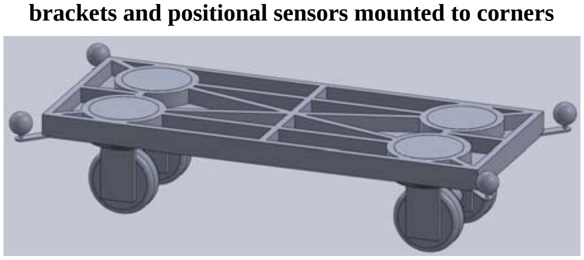

Figure 5. Lower platform with wheels in place

Third is the upper platform. The upper platform sits on top the lower platform covering and protecting the mechanical components of the vehicle while also providing the required base to interface with the desired cargo be it pallets, shipping containers, or people. The upper platform can be designed with a specific requirement in mind. Figure 6 shows an upper platform that is designed to hold a 20x8 foot cargo container. The modular design allows for the upper platforms to be interchangeable with the main vehicle allowing for one vehicle to be used with many types of cargo without having to compromise on how the cargo interfaces with the vehicle.

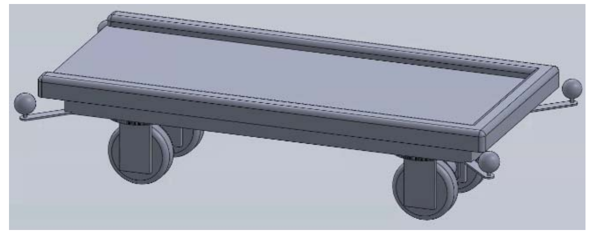

Figure 6. Compete vehicle with upper platform that is designed to handle large shipping containers

3. SENSORS

3.1 Guidance Methods

There are various methods for guiding the vehicles. These include wired navigation, guide tape, laser target navigation, inertial navigation, natural feature navigation, vision guidance, or geo-guidance.

Wired navigation is simply a wire carrying a radio signal embedded into the path the AGV is to traverse. The AGV has a sensor mounted below it that hovers just off the surface and picks up the signal from the wire, which allows for the vehicle to sense and follow the wire.

Guide tape is similar in principle to the guide wire but the guide tape carries no signal. Instead either a colored or magnetic tape is placed along the desired path and either a vision system or magnetic sensor read and follow the path laid out by the tape. There are advantages and disadvantages to both visible and magnetic tape. Visible tape, while it is cheap to install and make path adjustments, since it needs to be on the surface of the path to be viewed by the AGV, it can be damaged or dirty through daily vehicle and personnel activity. A system that uses a visible guideline for steering control has two ways it handles the guideline to control the steering. The first way, when the vehicle is moving at a slower speed it reacts to the error values of the vehicle with respect to the line. When moving faster, the controller uses the slope of the line to determine the required steering as waiting for error results could cause the vehicle to not be able to react in time at higher speeds. [J. Lee] The magnetic tape allows for it to be embedded into the path and therefore is not exposed to wear. However, having to carve out a channel and cover the buried magnetic tape results in a costlier install and makes it harder to change the path layout.

Laser target navigation uses a rotating laser emitter and sensor in tandem for distance detection that can be used for position tracking. The laser is reflected off reflective tags that are affixed to walls, poles, or other fixed obstacles, each of which corresponds to a known point in the workspace by the system. Therefore, by reflecting off the various reflective tags, the vehicle can triangulate its position and use that knowledge to plan and execute its motion based on the data that is collected and processed in real time. There are two types of laser sensors, modulated and pulsed. Modulated lasers have a larger range and higher accuracy over a pulsed laser with an angular resolution of 0.006˚. Pulsed lasers have an angular resolution of 0.2˚ and must be interpolated by the intensity of the reflection at each data point to reliably get an accurate location. For the system to work the vehicle needs to be in view of at least 3 environmental reflectors to correctly triangulate its position [38].

Inertial navigation uses a gyroscope that can, within an inch, detect the movement of the vehicle. It also uses transponders located in the workspace floor to verify the position of the vehicle. This system is flexible in that it can be used in a wide range of environments with or without the feedback [39].

Natural feature navigation uses range detecting sensors in conjunction with gyroscopes to read the layout around it and the vehicle triangulates its position using the natural features on the environment. It uses the data of its surrounding to develop the shortest possible distance to its destination since the system doesn't necessarily know the layout of its surroundings [39].

If the natural feature navigation did have full knowledge of its surroundings, then this system would be considered a geo-guidance system as it operates in the same way a laser guidance system works but without the reflective tags.

Vision guidance uses cameras to view their surroundings in a full 3D image and then builds a 3D map of the workspace. It can then match up its live view with that of its 3D map to be able to determine where it is in the workspace. It can also be programmed to recognize certain features such as obstacles or humans as to allow for the vehicle to stop or reroute [19].

3.2 Proposed Sensors for Control Method

The sensors that will be used on board and in the environment, will play a large role in the capabilities of the system. While the robustness of the control scheme is the foundation for autonomous control, an equally robust array of sensors is required to feed enough pertinent information that the system can make well informed decisions.

Vision sensors are those that use the visible light spectrum to capture an image for the system to process. Since a computer cannot inherently look at a picture and understand what it is displaying like a human can, the controller needs to be programmed to identify pertinent information from the video feed it is receiving. This can be as simply as recognizing a colored line on the floor and knowing it should follow it to recognizing certain shapes such as walls, other vehicles, or any other obstacles it could come across and knowing how to take evasive action. A vision system is very flexible but requires extensive programming work to get the most out of it [2].

Ultrasonic sensors can typically be used as proximity sensors since it is very easy to time the bounce of the signal and determine the distance of the object reflecting the sound waves. While these sensors would not be used for controlling the vehicle, they are instead used as a fallback safety system to warn and allow for the vehicle to stop if anything unexpected ever enters a predefined workspace of the vehicle. When dealing with large and expensive machinery, especially machinery that is moving autonomously, it is important to have multiple sensing and safety layers [23].

Infrared sensors can be used for tracking of the vehicle and positional sensing. While similar to the vision system, since these sensors only operate on the infrared wavelength, special infrared emitters and reflectors can be placed on the vehicles and in the environment to allow for positional data to be determined since the environmental emitters and sensors will always have a fixed and known location [24].

Radio frequency sensor picks up radio signals that are present. In the history of the

AGV, this sensor has been used to allow the vehicle to read and follow a wire that emits a radio frequency that is embedded into the floor that defines the desired path of the vehicle.

Magnetic sensors pick up on a magnetic field that is present. A magnetic sensor can be used in the same way that the radio sensor was used by reading the signal from a magnetically charged wire that defines a path for the vehicle.

Gyroscopic/force sensors can measure the forces that the AGV is experiencing due to acceleration. This can be used to gauge and control the acceleration and deceleration of the vehicle while also monitoring lateral forces that could be imparted by taking turns with a moderate speed.

Global Positioning Systems are another way to detect the position of the vehicle and is especially useful in an outdoor work environment that is exposed to more variables such as weather and time of day that can affect some of the sensors mentioned above.

All the above sensors can be used together to give an automated vehicle a plethora of instruments that allow for the vehicle to read and navigate its environment [25]. The sensors each have their strengths and weaknesses that must be considered when choosing the right sensors to design a control system around. It is also important to have built in fail safes and redundancies into the system such that control will not be lost should a sensor go down or an environmental condition affect the system. One example is if the lights go out in the workspace and the controller only operated off of vision sensors. This would cause the system to lose all input from the sensors. And while at that point one would hope that the controller is programmed to shut down in that scenario, there is a moment while all these vehicles would be trying to stop that they would be blind and at risk for collision. In this scenario ultrasound and infrared sensors can be used to protect against this situation. Infrared sensors are not impaired by the lack of light and use infrared emitters placed n the environment to determine its position. Ultrasound sensors rely only on sound waves to detect the proximity of objects from it. This could allow for the vehicle to detect any objects that would be in its vicinity and allow for it to maneuver in a way that it would be able to avoid the object although it is not able to 'see' it in the conventional sense.

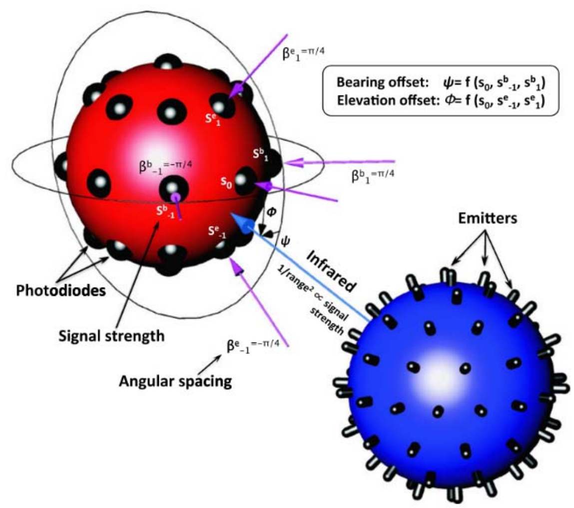

Figure 7. Diagram of 3-D relative positioning sensor for indoor flying robots [14]

The infrared sensor and emitter clusters depicted in figure 7 were developed for use on indoor flying robots [14]. However, the sensor design can be used with an autonomous vehicle control system. The design calls for a spherical array of infrared emitters and sensors.

In the figure below the blue and red spheres depict them respectively, however they are only depicted as two distinct objects to clearly show the interaction between the emitting and sensing portions of two sensors. The actual sensor is a sphere with both the emitters and sensors interspersed between each other. This allows for each vehicle outfitted with the sensor to not only read its environment but to also be able to be sensed by other vehicles and by sensors in the environment that monitor the positions of the vehicles.

When the sensor picks up a signal, it measures the intensity of that signal at each of the sensor nodes. It uses the three strongest signals and then triangulates the direction and uses the signal intensity to determine the distance the object emitting the signal is from the sensing object. This can be done since the geometry of the sensor sphere is known and the decay of the infrared light intensity can be experimentally found and then applied to calculating proximity.

4. CONTROL METHOD

The proposed control system is to use and build upon elements from previous control systems such that efficiency and reliability are increased.

A hybrid controller will be employed for the system having a main controller monitors all sensors, both environmental and those on each vehicle, and control the fleet of vehicles on a macro level with path planning and task queueing. Each vehicle will also be equipped with a controller able to read from its sensors and perform on board calculations and take independent control of the vehicle when either contact with the main controller is temporarily lost or for a reactionary maneuver that would take too long for the central controller to sense and react to.

The motivation for having multiple control layers for this system is to increase reliability of the system. With these vehicles being trackless, they are not hardwired into the control system and often rely on a Wi-Fi or other close ranged network signal that can fluctuate in coverage or suffer from slowdown when too much information is being transmitted. If control was handled purely from a central system, any network interference would cause an affected vehicle to stop and wait for either the signal to return or for a manual override.

The system will have a wide array of sensors, both onboard the vehicles and in the environment. The primary positioning sensor will be the 3D spherical emitter and sensor arrays. Each vehicle will have of these 3D sensors, on at each corner of the vehicle. This will allow for the sensors in the environment to be able to always have a clear view of at least one of the sensors regardless of vehicle orientation and allow for it to calculate the orientation of the vehicle. These sensors not only allow for the central system to read the position of the vehicles, but also allow the vehicles to read their position in the environment and allow them to read other vehicles that they have line of sight with.

The benefit of each 3D sensor is that it both emits and reads so that the information is always being shared both ways between the various systems. This allows both layers of the control system to independently track position and verify the data between them and allow for them to operate independently should one end fail or lose contact.

A GPS sensor could be used for each of the vehicles if the application has a large outdoor workspace where it would be uneconomical or impractical to cover the whole workspace with positional sensors.

The vehicle themselves are equipped with an accelerometer, load scale, positional and velocity tracking for each of the vehicles wheels, proximity sensors, and cameras.

The goal of the main system level controller is to be the manager of the entire system. It should be able to receive inputs from outside the system, such as user input for desired tasks, and then assign that to an active vehicle in the fleet. In assigning the tasks, the system needs to consider the positions of all the vehicles and their task status. It should assign new tasks as they come in such that it is carried out in the most expedited manner without affecting the flow of the rest of the tasks. The main system also calculates the path that the vehicle needs to take to carry out this task. The path planning is fully calculated before the task is assigned so that after the vehicle is assigned the task from the system, it could complete the task even if its connection with the main system is interrupted. While the task is being completed the two systems share all their sensor data to cross reference for verification and to monitor the progress of the vehicle.

The vehicle level controller is a simpler system that just takes the assigned pathing data and convert that to the required outputs for each of the four wheels. The vehicle controller also monitors onboard sensors that are mostly to monitor the surroundings for possible obstacles that would need to be avoided.

With four independently powered and rotatable wheels there are a lot of factors that go into the outputs for each of the wheels. Since they are not physically synchronized and are capable of being operated at different orientations, the precision of the controller is paramount since loss of wheel control when the vehicle velocity is sufficiently perpendicular to the wheels can cause damage or abrupt stops that could cause the load to be jolted loose. The two data points that are fed into the vehicles system are the desired Cartesian position of the vehicle along with its desired orientation. Each of these can be calculated as separate components of the wheel outputs then combined afterwards to get the independent signals for each wheel. This simplifies the calculations since the component of the wheel output for positional data is the same for each of the wheels. The orientation component of the wheel output is in a direction tangent to a circle that is centered on the middle of the vehicle and passes through each of the wheel's locations. This output is affected by the dimensions of the vehicle so it is very important that those are represented correctly in the system. Each of these components of the wheel output are linearly combined to give the required independent outputs for the wheel velocities and headings.

4.1 Positional Data

Having the vehicles use 3D relative positioning sensors they do not need to rely on more conventional methods such as GPS or wheel encoders, which each have shortcomings, lack of precision in some environments and error accumulation respectively. The only downside to using the 3D relative positioning sensors (3DRPS) is that you have to make sure that there are enough environmental sensors within line of sight of the vehicle in its workspace. With the vehicles and environmental sensors having a broadcasting and reading sensors, each can determine the location independently and cross reference for accuracy.

Each vehicle would be equipped with a minimum of two sensors in known locations on the vehicle. The environmental sensors are located in known locations within the vehicle workspace.

For the master system to determine the location of a vehicle it requires that one environmental sensor reads two sensors on the vehicle to resolve the 2 unknowns of location and orientation. If multiple environmental sensors can read the vehicle, then multiple reading can be cross referenced to improve reliability and reduce the possibility of a rogue reading or noise.

The vehicles have two possible methods for determining its location and orientation. The first way to determine its location is by reading its distance from a known location of an environmental sensor plus a compass reading (heading). The second method is to have one of the vehicle sensors read the locations of two environmental sensors.

The above methods for determining the vehicles location are the minimum data points required and more can be used for verification purposes.

4.2 System Outputs

The vehicle has a total of eight motors that work together to provide the desired vehicle movement. There are four drive motors (DM), one for each of the drive wheels which are controlled by setting a desired velocity. There are four rotational motors (RM), one for each of the drive wheels that control the angular orientation of each wheel indecently. They are controlled by giving a desired angle.

The vehicle will only need three inputs for the controller to sufficient define the required output. The inputs will be the desired x- y- coordinates of the location and the phi angle, which is the orientation of the platform, not the heading of the vehicle motion. The theta is resolved within the controller by solving the trigonometric relationship between the current vehicle location and the desired vehicle location.

The controller will use the desired values for the inputs, supplied from the main control system, and use a PID controller to determine how each will factor into the two output values for the vehicle motors. Each value will use feedback from sensors for each of the respective inputs to allow for maximum accuracy and responsiveness. Once the framework for the controller is built, the gain values for each input will be optimized to give the best balance between a smooth, yet responsive signal to the output motors. Since the controller can be adapted to vehicle size and environmental needs, the gains for the controller will need to be fine tunes for each application independently.

The velocity and angle for each of the four drive wheels are the result of the desired liner velocity and heading along with the desired platform orientation. Each of these events can be calculated separately then combined linearly to determine the final outputs for each of the wheels.

4.3 Vehicle Controller

The system for the trackless vehicles is a two-tiered controller that works in parallel. This consists of a master controller that oversees the entire system, and a local controller that is on board of each vehicle that carries out the plans of the master controller.

The higher-level controller is a system monitor and planner for the entire system. There are multiple facets to this controller.

First, this controller plans tasks and distributes them down to the individual vehicles. This is done by the controller taking a queued task in the system and deciding which vehicle will complete the task. This can be based on proximity or which vehicle was used last or many other parameters. The controller then creates a path for the vehicle from its current location to that where the task needs to be completed. The path is given in terms of x- and y-coordinates and the orientation of the vehicle (phi). These are all given with respect to time to control the velocity of the vehicle depending on loads such that it can safely stop given the range of its onboard sensors.

Second, the controller monitors all the sensors that are hardwired into its system. These are all the environmental sensors so that the controller can make informed decisions on path planning and current work flow. This can allow the system to read obstructions so that it can plan ahead of time instead of having the vehicle itself sense the obstruction and have to react locally.

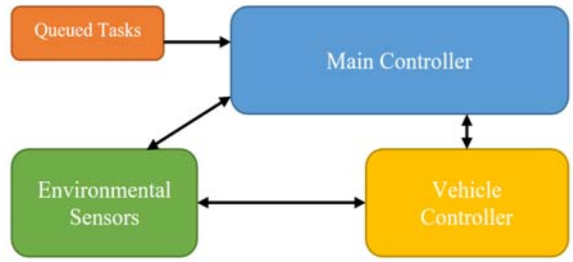

Figure 8. Flowchart for flow between controllers and sensors

Third, the controller receives all the sensor data from each of the vehicles and verifies that data with its own sensor data. Since the positional sensors have a component on both the vehicle and in the environment, the reading from each of the perspectives can be compared since they should ideally be reading the same value. The difference in value is compared to an acceptable tolerance that can trigger a shutdown if the error exceeds it. Since the controller can read the vehicle sensor data, it can make updates to the path should the vehicle encounter a local obstruction that the overall system did not account for when originally planning the path. This allows for the system to adapt in real time using data points from any of the vehicles. While the vehicles do not have to directly connect, the system can use data it receives from one vehicle and apply that information to any other vehicle that the system deems would benefit from the data.

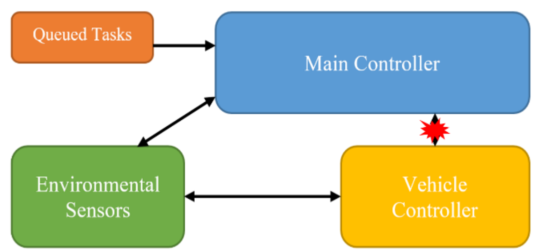

Figure 9. System with connection issues between main controller and vehicle

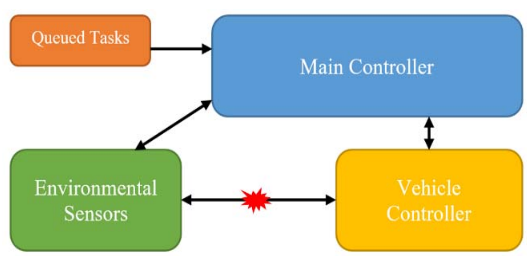

Figure 10. A signal error between the vehicle and environmental sensors

The vehicle controller is fully capable for operating a vehicle independently of the main controller. The only pertinent information the vehicle gets from the main controller is the path to a goal location. Having the vehicle contain a full suite of on-board sensors and processing capabilities allows for the vehicle to navigate the work environment once the path data is supplied to it. This allows for the vehicle to keep running even if the connection is lost with the main system for whatever reason. Once the vehicle reaches its desired goal position, if a connection is still unavailable from the main system, the vehicle will wait. While a major connection issue will cause productivity to stop in some capacity depending on the location of the connection issue, the main benefit on this is that intermittent connection issues will not force emergency stops or lead to vehicles losing control if they relied on the main signal for motor output signals. This can maintain a high uptime barring a major issue with the main controller. With most of the work offloaded and distributed to the vehicles, a vehicle controller issue is minimized to only the affected vehicle and will not impact the performance of any other vehicle in the workspace.

Besides a connection issues between main controller and vehicle, there are other issues that can be overcome by the layout of the system. The positional sensors that are employed for this system are 3D relative positioning sensors (3DRPS). The way these sensors work is that each sensor both emits a signal and reads the signals from other sensors. The 3DRPS are placed in known locations of the environment. This allows the environmental sensors to read the relative position of a vehicle and report that to the main system. This also allows the vehicle sensors to read the relative position of the environmental sensors and calculate their own location. Since the vehicle is having its position read from two sources, this creates a level of redundancy that can be used for verification purposes to increase accuracy, but also to allow for operation to continue if one of the signals is either unable to read or giving bad numbers. This can mainly be used to allow for the system to identify and ignore possible rogue values from the sensors without having the system have to stop. While this can be used to allow for operation to continue if there is a more permanent issue with part of the sensor network, it would be recommended that the vehicle only operate to finish its current task then remove itself from service to be inspected. However, even if a vehicle does have some kind of sensor error, the redundancy and parallel structure of the system allows for the vehicle to finish its task and exit the workspace versus having to perform an emergency stop while loaded in the middle of its work environment.

The main part of the vehicles controller is a PID controller that takes the desired path generated by the main controller, in terms of x- and y-coordinates and a phi angle (vehicles orientation) and calculates the required vehicle outputs in terms of wheel velocities and headings. The controller's feedback uses the sensor data from the 3DPRS to compare the vehicles current location with the desired location described by the intended pathing. The vehicle also contains other on-board sensors that are for local obstacle detection. There are three ways the vehicle controller uses the local obstacle data. If there are no detections or an obstacle is at a distance that is out of the vehicles path envelope, the vehicle will proceed uninterrupted. If the vehicle detects an obstacle that is along the planned path of the vehicle the controller can modify its path to avoid the object. If the vehicle detects an object within a proximity that the vehicle deems is nearing its stopping distance, it will tell the vehicle to stop. There will be a sufficient cushion to the stopping distance that the vehicle will err on the side of safety. The third condition of having the vehicle stop is only a result of extreme circumstances such as obstacles falling into the vehicle path or a moving obstacle that happens to be moving in the same direction the vehicle is attempting to deviate its path to.

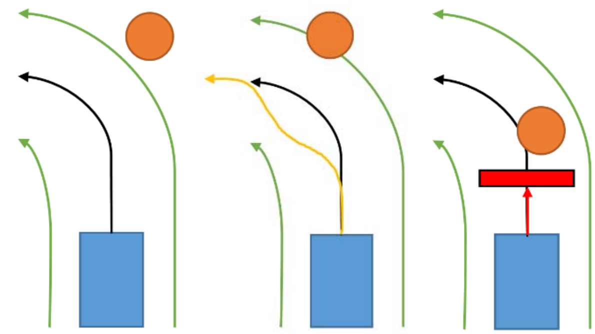

Figure 10. Obstacle detection and possible courses of action

The features of the main controller and vehicle controller come together to integrate with a multitude of sensors that allow for improved safety and efficiency over current applications of automated vehicles. This system can be deployed for virtually any application so long as there is enough infrastructure to establish a sufficient network of environmental landmark sensors. The main controller can be calibrated and scaled for any size and application from transportation of shipping crates in a shipping yard, moving raw material in a factory, or controlling a fleet of ride vehicles in an entertainment application.

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