Developing an AGV motion controller using simulation, emulation and prototyping

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Abstract—**Today transport systems using automated guided vehicles (AGVs) are centrally controlled and use a fixed infrastructure. Substantial efforts are therefore necessary if expansion or a change in system layout is required. In addition, incidents cannot be handled as part of the common routine. To overcome these problems a distributed anticipatory control method for AGVs is called for. According to this method every AGV is made responsible for its own path planning and collision avoidance.**

This approach requires a highly accurate controller to enable the AGV to follow its planned trajectory. This paper describes the development and testing of a controller for both positional and speed control. The AGV is modelled as a simple system with two steering wheel axles and an electromotor. The theoretical results obtained by using Matlab, are compared with results from testing the controller using an emulation model. Finally, the controller is implemented on an actual vehicle prototype, scaled 1:25, representing an AGV used for sea-container transport.

The results of this research can be used to develop a controller which is capable of achieving the required accurracy for automated, large scale, container transport systems.

Index Terms—**Automated Vehicles, Infrastructure, Intelligent Control**

I. INTRODUCTION

A. Research background and relevance

Every year there is a big growth in containerized transport throughout the world. In response to the growing demand for transportation and in order to reduce labour costs, Europe Combined Terminals (ECT) in Rotterdam has introduced a high degree of automation to its terminals. Their Delta Sealand terminal (1993) was the first fully-automated container terminal.

Delft University of Technology is involved in research on the design of a new generation of automasted container terminals. These have to be equipped in such a way that the anticipated arrival of Jumbo Container Vessels with a capacity of 8000 TEU (Twenty-Foot Equivalent Units) or perhaps an even greater capacity can be handled.

The three key elements of the logistic chain at a container terminal are the quay cranes, the container stack and the intra-terminal transport. Building quay cranes with higher capacity (thus shorter cycle times) is the task of mechanical engineers. In the near future, quay cranes with a capacity of 100 moves per hour will be possible (1960: 10 moves per hour). The container stack consists of an area where containers can be placed, and one or more fully automated cranes to handle them. Containers must be stacked in such a way that the stacking capacity is maximized and the container retrieval time is minimized.

Such fast quay and stacking equipment require a reliable, high capacity, transport system for the containers on the terminal. Although other transport systems are possible, here only systems using Automated Guided Vehicles (AGVs) are considered. Earlier research presented a method for the design of multi-AGV systems and control of their operation.

B. Automated transport on container terminals

Today transport systems using automated guided vehicles are centrally controlled and use a fixed infrastructure [1]. Substantial efforts are therefore necessary if upscaling, system merging or a change in system layout is required. In addition, incidents cannot be handled as part of the common routine. In case of systems with a variable number of vehicles and open infrastructure, central control is impossible. The design, evaluation and implementation of multi-vehicle systems are very difficult and expensive tasks. The challenge is to develop decentralized control mechanisms to make better use of the scarce and expensive infrastructure, improving transportation performance and obtaining a fast and generic method for designing, implementing and evaluating multi-vehicle systems.

In production systems Automated Guided Vehicles (AGVs) are commonly used for transportation purposes to reduce costs, increase capacity, minimize damage, structure procedures, and to reduce the number of errors. Moreover, the possibility of connecting the automated transport system to other automated systems is an important issue.

There are various ways to guide AGVs, such as induction wires in the floor, or reflective lines on the area where the AGVs operate, but this means that changing the layout of the system requires a substantial effort. In the so called free-ranging approach, using laser guidance or a combination of odometry and a grid of transponders, the paths are prescribed in software only. However, despite the routing flexibility

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obtained the actual trajectories during operations are usually fixed. These systems work very well if the number of vehicles and the number and location of potential conflicting points are limited and vehicle speed is relatively low. In case of complex layouts and many vehicles this way of working may restrict the system performance.

C. *Simulation, emulation and hardware in the loop*

Discrete event simulation has proven to be an effective tool to study the performance of logistic systems and to aid in their design. Today, due to the growing scale and complexity of these systems, distributed simulation is needed.

For the study of AGV systems, a discrete event simulation model of an AGV is a simple model which consumes time, based on the distance between the start and end, and the given velocity of the AGV.

Instead of testing real equipment, which can be dangerous and costly, emulation is used to model the relevant characteristics in a simulation environment. The emulation model describes the AGV's position in time, given the steering angles of front and rear axles, and the signal to the motor. This simple mathematical model uses only the dimensions of the modeled AGV and its mass.

Hardware in the loop means that real equipment is connected to the simulation environment. In the test the real equipment is a prototype of an AGV which consists of a modelcar with servo's for driving and steering both axles, sensors for odometry and an Intel processor based computer with a wireless network card.

D. *The AGV laboratory*

The section Transport Technology and Logistic Technology has a laboratory with mini-AGVs, build to a 1:25 scale of a real container transporting AGV (18 meter). In the laboratory issues can be addressed not covered with simulation.

The mechatronic layer in the control software translates the computer calculated trajectories in the signals for the servo's and translates the sensor data in useful status information.

Communication between the computer(s) running the simulation model and the AGV-computers is established by a wireless network. Issues like communication delay or even failure can be studied.

Real hardware will not behave ideally; friction between tyres and floor, for instance, will result in more complex behaviour than the emulation model can describe.

Stability of software systems, the effects of failures, etcetera can be studied in a much more realistic environment than in just a simulation model.

II. SYSTEM DESCRIPTION

A. *Simulation environment*

Previous research [2] resulted in a distributed architecture for the simulation environment. A set of simulation models as shown in figure 1 represents the quay side operation of a container terminal.

For the control system, a three-layer model is adopted, consisting of a logistic layer, a traffic layer and a mechatronic layer.

The simulation environment can be used to control the complete terminal operation. Optimization of the cooperation between the different types of equipment, cranes and AGVs, is part of the research. Cooperation consists of coordination in both the time and space domain.

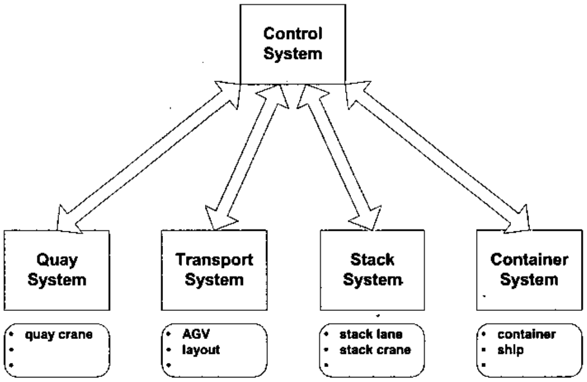

Figure 1 The five member models with some important object-classes

B. *Hardware in the loop*

The virtual environment presented in the previous paragraph is used in the AGV laboratory. In the lab, the only modification is the replacement of the simulated AGVs by an actual (prototype of an) AGV. The simulation model of the AGV is used by each AGV to calculate its own internal state. Furthermore, the Local Positioning System [3] consists of a digital camera system which provides accurate positional information for each AGV; this data is available on the wireless network.

The simulation model on the AGV has to run in real time. This requires some synchronization of the simulation clock with the 'world-clock', also known as the wallclock time. When the simulation is running real time, its scheduling capacities can also be used to establish the poll frequencies for the actuators and the sensors in the mechatronics layer.

III. AGV CONTROL

A. *Trajectory tracking control*

To get to a desired destination the AGVs need to be able to follow a predefined trajectory that defines the desired position as a function of time. This trajectory does not only define the string of coordinates the center of the vehicle has to follow, but also the angle between the AGV's centerline and the direction of the path, know as the crabbing angle, to gain an increased maneuvering capability.

To correct any deviations from the desired trajectory the vehicles require a controller that adjusts the steering angles and speed of the wheels. The task of this controller has been split up into two parts. The first part involves the minimization of the lateral error by controlling the steering angles, and the second part consists of the minimization of the longitudinal error by controlling the speed of the vehicle. Figure 2 shows how these error are defined.

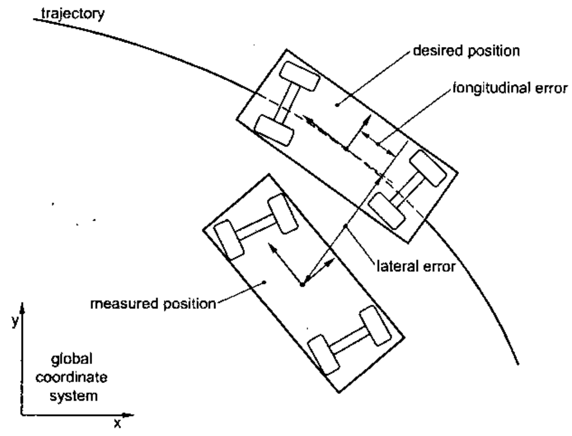

Figure 2: Errors that occur when the measured position deviates from the desired position

In order to construct a relationship between the controlled variables and the motion of the vehicle's center, a bicycle model has been adopted. In the bicycle model each axle has been replaced by a single wheel that pivots around the axle's original center position, as illustrated in figure 3. This figure also shows the steering angles of the front (α_{1d}, α_{1m}) and rear axle (α_{2d}, α_{2m}) and the angle of the vehicle's body with respect to the global coordinate system (θ_d, θ_m).

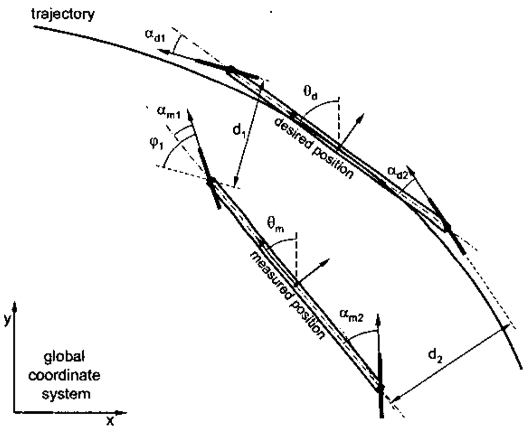

Figure 3: Simplified bicycle model of the AGV

Due to the relatively low operating speeds wheel slip resulting from side forces is not considered. This entails that there will be no velocity component perpendicular to the main axis of the wheels. Furthermore, in the absence of wheel slip the movement of the vehicle can be determined by kinematic relations.

B. Controlling the steering angles

Minimization of the vehicle's lateral error will be accomplished by letting each wheel individually steer towards its desired position. If both wheels reach their projected positions, which can be calculated from the current position on the trajectory and the desired crabbing angle, the lateral error of the vehicle's center is reduced to zero. In effect each wheel will get its own controller that adjusts the steering angle (α_{mi}) to minimize the lateral distance (d_i) between the projected and actual wheel position.

The rate of change of d_i is determined by both the wheel speed and φ_i, which represents the difference between the desired steering angle and the actual or measured steering angle. This relation can be written as follows:

$$\dot{d}_i = -v \cdot \sin\varphi_i \;\; where\; \varphi_i = \theta_d + \alpha_{di} - (\theta_m + \alpha_{mi}), \quad (i = 1,2) \qquad (1)$$

Only φ_i will be used to make the AGV track its trajectory because the speed will vary to correct for longitudinal errors. As a result, the speed is considered invariant for the lateral control problem, what will result in an adaptive controller with different settings for varying speeds.

Assuming that the AGV will stay close to the desired position, the required correction angle φ_i is expected to remain small. Under this assumption equation (1) can be linearized to:

$$\dot{d}_i = -v \cdot \varphi_i \qquad (2)$$

The front (α_{m1}) and rear (α_{m2}) steering angles are individually controlled by a servo. Both servos are considered black boxes that adjust the output angle to the desired position. The time it takes to adjust the angle is approximated by a first order system with a delay time τ_s.

To reduce the lateral error, a feedback loop has been added to the system. In this feedback loop the controller sets a new angle (φ_c) to counteract the measured lateral error. The complete model of the control system is given by the block diagram of figure 4.

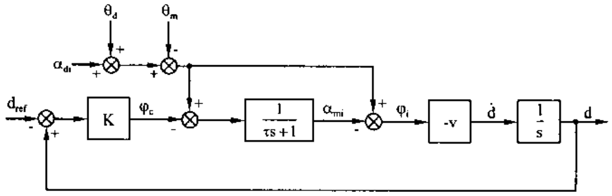

Figure 4: Block diagram of the lateral control system

From this block diagram the transfer function describing the relation between the reference distance d_{ref} (which will be set to zero) and the lateral distance d can be written as:

$$H_{lat,cl}(s)=\frac{d(s)}{d_{ref}(s)}=\frac{\frac{Kv}{\tau}}{s^2+\frac{1}{\tau}s+\frac{Kv}{\tau}} \qquad (3)$$

This is a second order function that is comparable to the general second order equation:

$$H(s)=\frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \qquad (4)$$

where ω_n is the undamped natural frequency and ζ is the damping ratio.

This comparison leads to the following relations between the parameters of the lateral control system and the natural frequency and damping ratio:

$$\omega_n=\sqrt{\frac{Kv}{\tau}} \qquad \zeta=\frac{1}{2\sqrt{Kv\tau}} \qquad (5)$$

The responses of the general second order system, which are characterized by both natural frequency and the damping ratio, are commonly known [4]. After viewing these responses a damping ratio of $\frac{1}{2}\sqrt{2}$ was chosen. This produces a fast response with an allowable overshoot and sets the controller gain to:

$$K=\frac{1}{2v\tau} \qquad (6)$$

This gain will be used for both controllers of the front and rear axle.

In this case both systems for the front and rear axles are considered independent. Although there will actually be interaction between the controllers through the measured angle of the vehicle, it is expected that if the AGV stays close to its trajectory, the mutual influence will be small. The actual gained controller performance will be established later using an emulated model.

C. Controlling the vehicle speed

As the AGV adjusts its steering angles to stay on its predefined trajectory, the actual traveled distance will start to vary from the expected traveled distance. This difference results in a growing longitudinal error. To correct this error the AGV will need to make speed corrections. Furthermore, to be able to maintain the desired speed the motor's power supply has to compensate for varying mechanical resistances resulting from changing running surfaces ranging from smooth to very rough floors.

In order to develop the controller that minimizes the longitudinal error and that keeps the actual speed close to the reference speed, a model of the vehicle's driveline is presented. The driveline consists of two identical electric DC motors each driving an axle through a transmission. One motor powers the front wheels while the other motor drives the rear wheels. As both motors are identical and, in the non slip situation, will run at virtually the same speed, both motors are modeled as a single unit that produces twice the amount of torque of a single motor.

The torque of a single DC motor (T_m) is related to the voltage (U) supplied to the motor and the shaft speed (ω) as follows [5]:

$$U=I\cdot R+k_b\cdot\omega \qquad T_m=I\cdot k_T \qquad (7)$$

where k_b and k_T are motor constants, and I and R represent the armature current and resistance respectively.

A gearbox with reduction i transfers the torque of the motor to the wheels. The output torque of the output shaft directly acts on the wheels, which results in a driving force that is applied to the floor. The total drive force (F_d) generated by both motors and the motor shaft speed is equal to:

$$F_d=2\cdot\frac{T_m\cdot i}{r_{wheel}} \qquad \omega=\frac{v\cdot i}{r_{wheel}} \qquad (8)$$

where r_{wheel}, ω and v represent the wheel radius, angular motor shaft velocity and vehicle speed respectively.

Finally, the drive force and frictional force (F_w) both relate to the acceleration as follows:

$$m_v\dot{v}=F_d-F_w \qquad (9)$$

where m_v represents the mass of the vehicle and container.

If equation (7), (8) and (9) are combined, the model for the motor and vehicle speed can be represented by the following block diagram:

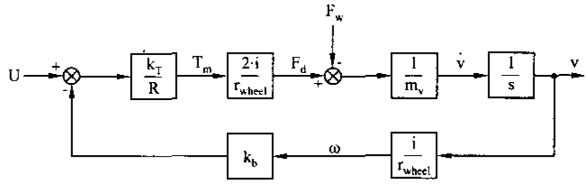

Figure 5: Model of motor influence on vehicle speed

The vehicles in this system will directly feedback the longitudinal position error (e) to make a correction to the voltage supplied to the motors. When a controller is added to the system, which directly affects the plant illustrated in figure

4, the block diagram of the closed loop system becomes:

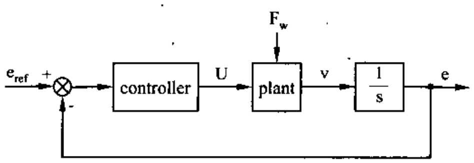

Figure 6: Correcting the longitudinal error with feedback control

The open loop transfer function of the system the controller acts on is equal to:

$$H_{long,ol}(s)=\frac{e(s)}{U(s)}=\frac{C_1}{s(s+C_2)}$$

$$with \quad C_1=\frac{2ik_T}{Rr_w m_v} \quad and \quad C_2=\frac{2i^2k_bk_T}{Rr_w^2 m_v} \tag{10}$$

A PI controller was selected to control this system. The system requires an integrating action to prevent static offset when a ramp function is applied. As the AGV will be commanded to run at set speeds, ramp functions will be common appearance at the input of the system. The controller has been given no differentiating action because the open loop system offers sufficient phase margin at the desired crossover frequency. Furthermore, a differentiating action will have the undesired effect of amplifying the noise generated by the positioning camera.

With the PI controller in place the transfer function of the block diagram in figure 6, describing the relation between the reference distance e_{ref} and the traveled distance e, can be written as:

$$H_{long,cl}(s)=\frac{e(s)}{e_{ref}(s)}=\frac{KC_1\left(s+\frac{1}{T_i}\right)}{s^3+C_2s^2+KC_1\left(s+\frac{1}{T_i}\right)} \tag{11}$$

The parameters of the controller have been tuned to generate an acceptable step response with little overshoot to prevent the vehicle from reversing and an acceptable settling time. With the given model parameters shown in table 1 a gain (K) of 200 and an integration time (Ti) of 5 generate the desired response. Figures 7 and 8 illustrate the resulting bode plot of the open loop system and the step response of the closed loop system.

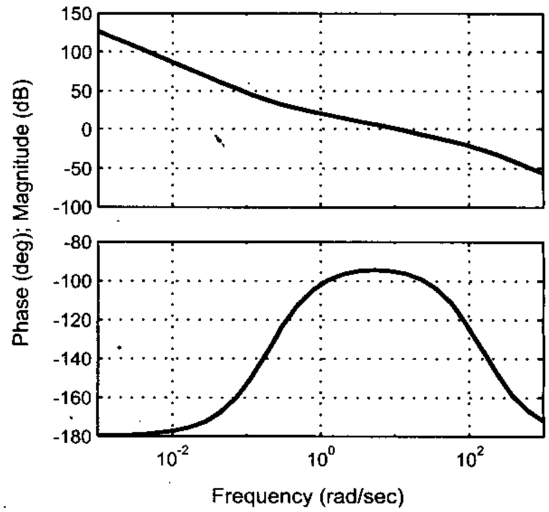

Figure 7: bode plot of the open loop system

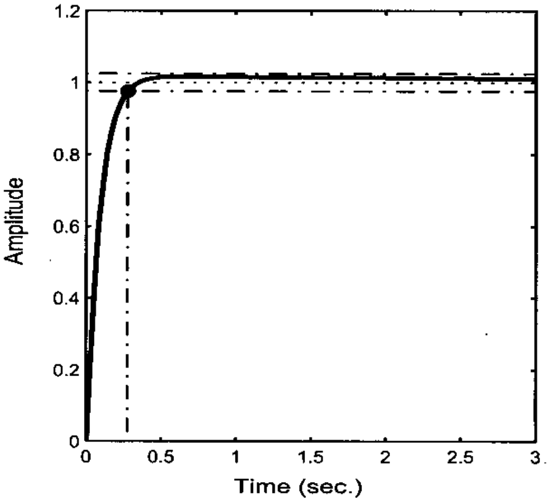

Figure 8 the step response of the closed loop system

TABLE 1: MODEL PARAMETER FOR LONGITUDINAL CONTROL

k_b	k_T	R	i	r_w	m_v
$1.30\cdot10^{-2}$ Vs/rad	$8.83\cdot10^{-3}$ Nm/A	1.00 Ω	39.70 -	$2.85\cdot10^{-2}$ m	3 kg

IV. RESULTS

A. Emulation model

To test the performance of the AGV motion controller, an emulation model is used to replace the actual hardware that the control logic will interface with. The models interface is set up in the same form as if it were connected to the real system. Because emulation only replaces a part of the real system with a model, emulation has more credibility than simulation when it comes to using the model to predict the performances of the real systems. The controller is coded into an AGV control program using the Delphi programming package.

A discrete event model of the real world AGV was build using Delphi in combination with the TOMAS simulation package [6]. The resulting program defines several moves of the AGV on different kinds of paths it has to follow, includes the dynamics associated with the servo's and the motors of the AGV and also models the observation system for position determining. The emulation models task in this program is to process the signal coming from the controller with the associated servo and motor dynamics to determine the new state of position and velocity. The emulation study conducted with this program enables testing performance of the real AGV running on a defined trajectory with the developed control system. Several measures of performance were used for this purpose.

B. *Experiments*

Insight into the controller performance was obtained through observation and analysis of the lateral, longitudinal and orientation error in the AGV's position during a move. Simple experiments were initially conducted for straight paths and lane changes. The performance measured during these experiments were compared with the expected theoretical values. To measure the overal performance of the complete set of controllers more realistic trajectories were introduced consisting of a number of straight lines and bends.

The results for the lateral control show that the time domain performance measures closely match the response of a second order system. For low values of the controller gain the system behaves like an overdamped or a critically damped system, giving a damping factor of greater than or equal to one. For higher gains the system response is comparable with the underdamped second order system response. With increasing gains the overshoot increases which is as expected. The system's time period and damping also matches the theoretically expected results.

The speed control response is not a general second order response, so the results from the emulation cannot be compared with a general second order system as done with the lateral controller. Therefore, experiments were conducted with the emulation model on a straight path to see if the best response (with smallest error) is the same as is expected from theory. A stable response with acceptable error and settling time can be reached if the right gain value is used. At very high values of the integrating action, the emulation results show that for changes in the AGV speed, the error response grows without bound and the system becomes unstable, which results in a back and forth movement of the AGV. When integrating action is lowered the system will become more stable but oscillations will continue until it is sufficiently small. These results are consistent with earlier calculated theoretical results.

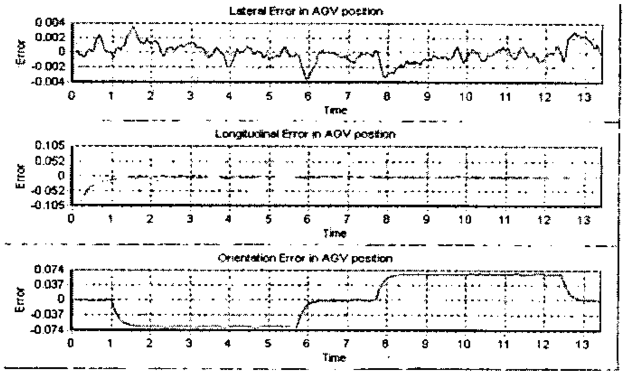

Figure 9 lateral, longitudenal and orientation error of the AGV position on a realistic trajectory.

When the position and velocity controllers are combined together, the response of the AGV system can no longer be predicted with a second order system analysis. A more practical approach would be to look into the errors in lateral, longitudinal positions and orientation of the vehicle and observe the performance of the system. To accomplish this a test was done with several trajectories. These trajectories consists of bends and straight-line combinations with predefined angles and lengths. Effect of each of the following parameters on the system controllability is studied for these realistic trajectories. An example of the observed errors during an experiment is found in figure 9.

C. *Prototyping*

The performance of the controllers for the emulated AGV is satisfying. Therefore, the next step in this project is to implement the controllers on the AGVs in the AGV laboratory. Not all the laboratory experiments have been conducted yet, but preliminary tests show that the concept does work. The performance of the completed laboratory work will be reported later.

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