SENSOR-BASED COLLISION AVOIDANCE FOR ROPE-SUSPENDED AUTONOMOUS MATERIAL FLOW SYSTEMS

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Abstract: A novel approach to collision avoidance concerning unknown dynamic obstacles is presented for a material flow system using an overhead travelling crane. The task involves the tracking of a desired trajectory derived from a path planning module based on a global map containing all static obstacles. The crane has been upgraded with three ultrasonic sensors which detect dynamic obstacles on the desired trajectory. Experimental results obtained from an implementation at the overhead travelling crane demonstrate the efficiency of this prototype of an autonomous material flow system. *Copyright 2005 © IFAC*

Keywords: Obstacle detection, ultrasonic detectors, robotics, trajectory planning

1. INTRODUCTION

In the last decade, automated transport systems for heavy payloads using a rope suspension have become more and more important. The overhead travelling crane of the Department of Measurement, Control and Microtechnology (MRM) has been reengineered as a prototype of a material flow system equipped with a control system providing active damping of load oscillations as well as tracking of user-specified trajectories in known environments (Aschemann, 2002). (Miyoshi and Terashima, 2004) presented an optimal path planning algorithm that accounts for static obstacles. In order to enable the overhead travelling crane to operate autonomously in a changing environment, dynamic obstacles have to be considered as well. Consequently, the focus of this paper is on the development, the integration and the implementation of a collision avoidance module for dynamic obstacles.

Global path planning calculates a path in the 3D-workspace between the starting point and the destination point, which can be given either by a user or a supervising material logistics program. Therefore, a global map representing the environment of the overhead travelling crane with all known static obstacles has to be established. Then, an optimal path is calculated in this global map by an extended A*-search algorithm between the two specified points (Wecker, *et al*., 2003). In the case of a dynamic obstacle the collision avoidance module has to guarantee that the crane load either stops safely in front of it or detours this obstacle. As a result, the automated overhead travelling crane is enabled to transport standard pallet boxes autonomously in the given workspace.

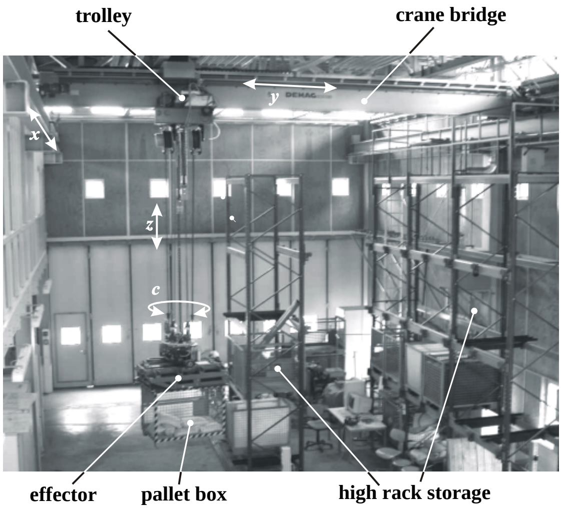

Fig. 1: Overview Crane

For this transportation task the travelling crane is equipped with four main axes (fig. 1): the three axes x, y, z for the crane load position and the c-axis of the effector for the orientation of the crane load w.r.t. the z-axis.

This effector has the designed capabilities to operate both the floor storage and the high rack storage.

2. INTEGRATION CONCEPT

In order to create a material flow system based on an overhead travelling crane, additional modules originally developed for autonomous robots are required.

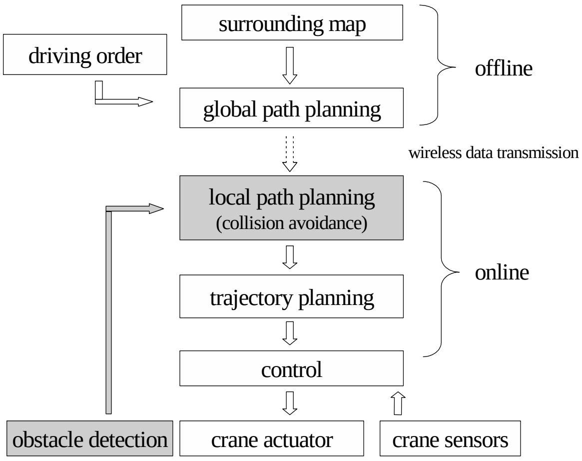

Fig. 2: Integration concept with existing and additional (grey) modules

Fig. 2 shows a block diagram of the integration concept for the corresponding modules. As for the path planning, the first step consists in generating a global map including all known static obstacles. This map may also includes additional information about known limits, e.g. limits concerning the maximal load height in an area accessible for person or preferred path segments to move on.

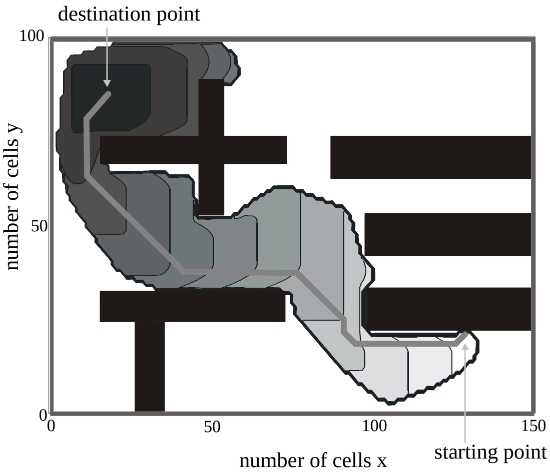

Fig. 3: Exemplary path calculation using the A*-search algorithm

The driving order can be given either by a user or a supervising material logistics program. By means of this global map stored in the computer as well as the specification of a starting point and a destination point, an optimal path for the crane load is calculated with the A*-search algorithm (fig. 3).

The optimal path results in a set of interpolation points, which are to be connected by smooth functions of time, e.g. Hermite-splines. The optimal trajectory, i.e. the desired load position as a function of time, is directly utilised for the decentralized position controls of the main axes as long as no dynamic obstacles occur (Aschemann *et al.*, 2000). During trajectory tracking, the control module provides high tracking accuracy as well as damping of load oscillations.

In order to use the automated crane in areas that are accessible for person, safety regulations demand a collision avoidance module. This module has to ensure that the pallet box does not hit any unknown dynamic obstacle being close to the desired trajectory.

3. LOCAL PATH PLANNING

As for local path planning, two principle strategies can be applied if a dynamic obstacle is detected by the ultrasonic sensors when the pallet box is tracking the desired trajectory (fig. 3).

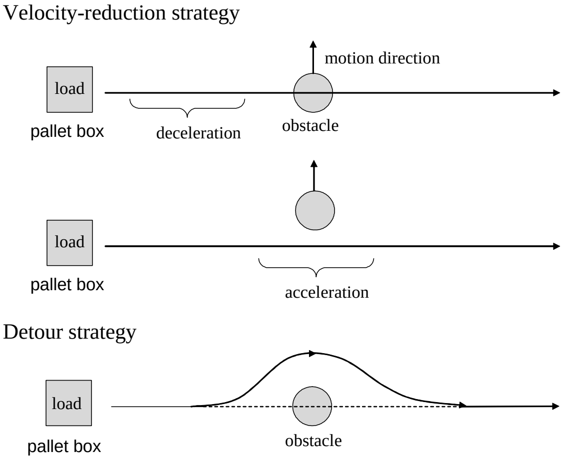

Fig. 4: Strategies at local path planning

The first approach, the velocity-reduction strategy, involves a reduction of load velocity on the path related to the reference trajectory. This is achieved by taking advantage of the time-scaling technique. In the worst case the pallet box comes to a halt. The tracking of the original reference trajectory is continued as soon as the detected obstacle has left the critical area. It is important to note that a new calculation of the trajectory is not necessary.

The second strategy, the detour strategy, can be advantageously employed if the obstacle obstructs for a longer time period the path related to the original desired trajectory. The transport of the pallet box can be pursued by calculating a new, collision-free trajectory segment that first detours the considered obstacle and second enables a restart of the tracking of the original desired trajectory. As a result, it is necessary to calculate the connecting detour trajectory. In this paper, the focus is on the velocity-reduction strategy, whereas the second strategy will be considered by the authors in future research.

4. ULTRASONIC SENSOR SYSTEM

4.1 Sensor Configuration

The ultrasonic sensor used for the measurement of the distance to the obstacle uses on the impulse-echo method. Here, the distance sensor operates as both transmitter and receiver. The sensor emits very short ultrasonic impulses and, after switching into the reception mode, receives the impulses reflected by the obstacle. These short impulses are generated by means of a piezo-crystal. If the crystal is appropriately triggered by a rectangular voltage, this voltage is transformed mechanically into an ultrasonic-impulse. Inversely, the same principle is used for the reception of the ultrasonic-impulse: the reflected ultrasonic-impulse is transformed by the piezo-crystal into a corresponding electric voltage.

To determine the distance to an obstacle, the running time of the emitted impulse has to be measured. Then, the distance s results in

$$s=\frac{1}{2}\cdot c\cdot t \quad , \quad c=\sqrt{\kappa\cdot R_S\cdot T}\ . \qquad (1)$$

Here, c characterizes the speed of sound in the air – depending on the temperature T, adiabatic exponent $\kappa = 1.4$ and gas constant $R_S = 286.9$ J/(K·kg) – and t represents the measured running time of the ultrasonic signal. The speed of sound at a temperature of $T = 293$ K , i.e. 20°C, has the value $c = 344$ m/s. In this measurement, the intensity of the reflected impulse depends on the material properties and on the distance to the object.

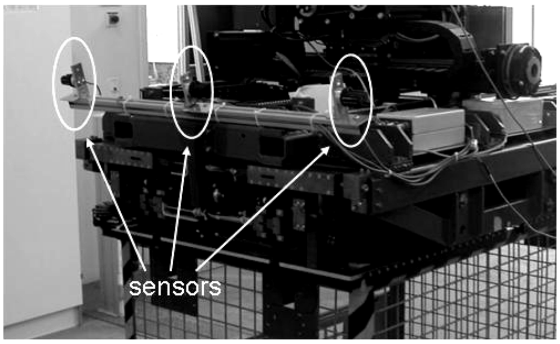

Fig. 5: Sensor configuration

The chosen ultrasonic sensor is characterized by its compact and robust construction. Additionally, a signal amplifier has already been integrated into the housing. For obstacle detection three ultrasonic sensors are arranged on a frame that is attached to one side of the effector as depicted in fig. 5.

The controlled rotatory axis, the c-axis, ensures that the frame supporting the three sensors is always orientated in the current movement direction.

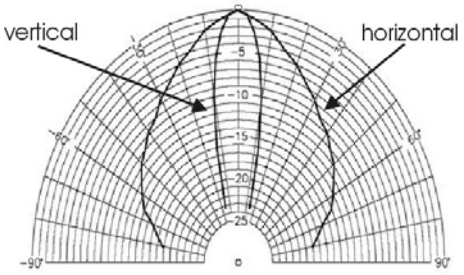

Fig. 6: Vertical/horizontal emission patterns

The chosen ultrasonic sensor exhibits different emission patterns in vertical and horizontal directions (fig. 6). Three of them are necessary to guarantee a complete covering of the region of interest in front of the pallet box without any gaps (fig. 7).

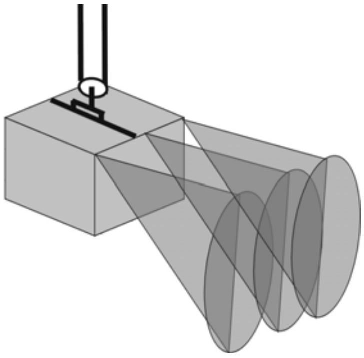

Fig. 7: Detection range of the sensors

Each sensor is triggered with a rectangular voltage signal to emit the ultrasonic-impulse. Depending on the distance and, consequently, on the delay of the impulse, an alternating voltage signal is received from the ultrasonic sensors.

4.2 Interaction between several sensors

For an efficient collision avoidance, a single ultrasonic sensor is not sufficient. On the other hand, when using several sensors next to another, two main problems emerge. A first problem stems from the fact that, when several ultrasonic sensors are triggered synchronously, the received echoes cannot be clearly distinguished and assigned to the different sensors. As a result, it is not possible to determine the exact distance to the obstacle. The second problem results from cross talk when ultrasonic sensors that are not appropriately shielded cause interferences.

One possible solution would be to trigger the three sensors not synchronously but separately, so that the sampling frequency is reduced. In this configuration there are three ultrasonic sensors mounted parallel at a distance of 45 cm from each other at the effector. As a result, the sampling time is approximately 105 ms for a complete measurement cycle using all the three ultrasonic sensors.

5. EVALUATION UNIT DESIGN

5.1 Data Processing

The evaluation unit consists of a digital part and an analogue part (fig. 8). The whole measurement process is controlled and supervised by a microcontroller, which also serves as a communication interface to the control structure. The analogue part is responsible for the signal processing from the ultrasonic sensor and the adaptation to the TTL-input of the PLD (Program Logic Device).

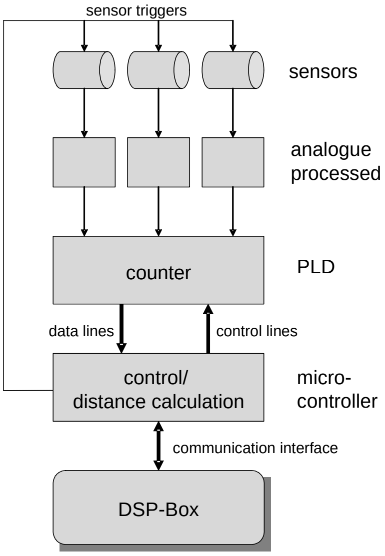

Fig. 8: Architecture of the evaluation unit

The analogue part of the whole equipment is first considered here. Fig. 9 shows the schematic function of the analogue switching structure.

The ultrasonic sensor is triggered by the evaluation unit with a rectangular voltage signal. The internal electronics of the sensor emits a ultrasonic wave at a frequency of 45 kHz, which is reflected by an obstacle and received by the ultrasonic sensor with a delay depending on the distance. The detected signal at the ultrasonic sensor output is also an alternating voltage at a frequency of 45 kHz.

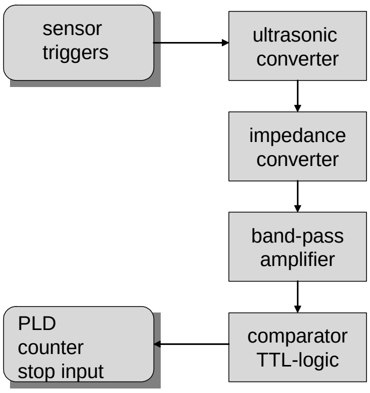

Fig. 9: Analogue program cycle

To determine the distance to the obstacle, it is necessary to know the delay of the ultrasonic wave. For this, the voltage signal should be processed in a way that it can be digitally analysed by a PLD. Moreover, the analogue part is supplied with the output signal of the ultrasonic sensor using an impedance adaptation. In order to damp possible interferences on the signal, it is filtered with help of a band pass filter with high performance.

To ensure that echoes with low intensity can be detected, the filtered signal must be amplified before the next step. An easy adaptation of the ultrasonic sensors to the environment and its disturbances becomes possible when a comparator with a switching threshold is used. This comparator produces a digital signal in the TTL-standard at the output of the analogue part.

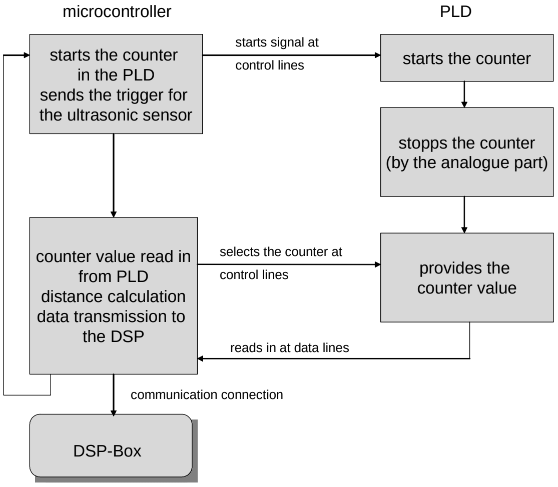

Fig. 10: Microcontroller program cycle

The digital part of the evaluation electronics consists of two components:

1) the PLD to determine exactly the delay of the ultrasonic wave,

2) the microcontroller which is responsible for the control of the whole measurement process of the ultrasonic sensors, the calculation of the distance to the obstacle and the communication with the DSP.

In the PLD accurate counter modules were realised with a time resolution of 50 µs, which corresponds to a distance resolution of 0.8 cm. The PLD analyses the processed signals of the analogue part and stores the reading into its internal registers. An additional function is integrated that makes it possible to damp the disturbances caused by the sensor arrangement. These disturbances result from the reflections at the fixation of field installation of the ultrasonic sensors and can be avoided with an appropriate delay time at the beginning of the measurement. As soon as the microcontroller starts to measure, a trigger impulse is emitted to the ultrasonic sensor and at the same time to the PLD. In this PLD the delay is counted until the stop signal of the analogue part reaches the PLD. After this the current reading is stored and can be read by the microcontroller. When a new measurement cycle starts, the memory of the counter is deleted and the counting starts anew.

The microcontroller is responsible for the coordination of the whole measurement process. First the measurement of the distance is realised with help of ultrasonic sensors. For that purpose the trigger impulse is emitted to the ultrasonic sensor and at the same time the counter in the PLD starts. After a time of 35 ms resulting from the maximum possible distance between the obstacle and the ultrasonic sensors, the microcontroller reads the stored readings c_{value} from the PLD. The maximum distance for this ultrasonic sensor is 5.5 m. The counter of the PLD has a resolution $t_{resolution}$ of 50 µs. The microcontroller converts the reading into a distance value in meter with the following formula

$$s = \frac{1}{2} \cdot 344 \, \tfrac{m}{s} \cdot c_{value} \cdot t_{resolution} \, . \qquad (3)$$

This measurement cycle is repeated every 35 ms.

5.2 Data Transmission and Synchronization

Both the microcontroller and the DSP have an integrated serial interface RS 232, which is utilised for the communication between each other. The distance value in meter is transmitted to the DSP with its own protocol.

First, the received data has to be synchronized with the cycle time of the control. At the same time, the correctness of the data is checked. The data of each sensor is transmitted to the DSP when the maximum delay time of the impulse (35 ms) is elapsed. However, both control module and trajectory generation module are subject to a shorter sampling time of 5 ms. Consequently, an additional coupling module is required. This coupling module is triggered by the serial interface, i.e. each time when a data transmission from the evaluation electronic to the DSP takes place, the coupling module is called. The coupling module checks the correctness of the received data and delivers the current distance value every 5 ms to the control module according to its sampling time. This distance value is maintained until a new value is received. This process is repeated for all distance values delivered by the three ultrasonic sensors.

6. VELOCITY-REDUCTION STRATEGY

If no obstacle is detected by the ultrasonic sensors within a distance of 3.5 m, the trajectory is tracked without changes. However, when the ultrasonic sensors detect an obstacle within a distance of 3.5 m to the load, its velocity is reduced until the distance to the obstacle reaches 1.2 m and the load stops.

Every 5 ms the trajectory generation module provides the desired position, the desired velocity, the desired acceleration and the desired jerk for the next control cycle. If the velocity of the load has to be adapted due to a detected dynamic obstacle, all the desired values mentioned before have to be modified consistently.

The adaptation of the velocity is achieved by time-scaling. The reference time, which is used as input of the trajectory generation module for the calculation of the desired values, is slowed down in dependence on the current distance value delivered from the ultrasonic sensors according to fig. 11. This affects not only the desired positions but also all the corresponding time derivatives.

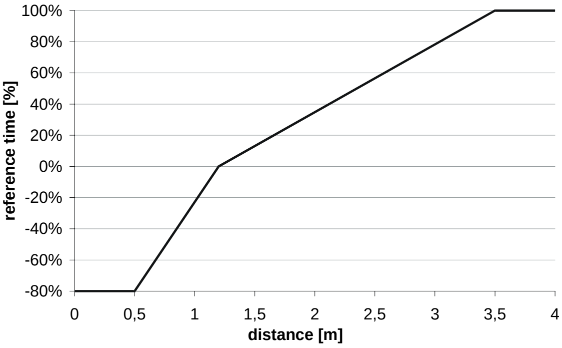

Fig. 11: Reference time depending on the distance

If no obstacle lies within a distance of 3.5 m, the reference time is not modified and the trajectory is tracked as planned. Using these methods, collision avoidance for detecting dynamic obstacles with help of ultrasonic sensors on the path of the load is thus successful, so that the load halts at a safe distance of 1.2 m.

If an obstacle is detected at a distance of less than 1.2 m, e.g. if a person coming from a side walks into the detecting area of the ultrasonic sensors, the reference time shifts into the negative time. As a result, the crane load goes some distance back on the path. The crane bridge returns until there is a safe distance to the obstacle of 1.2 m. As a result, the braking distance of the load can also be shortened because a greater reset force through the larger rope deflection can be applied to the crane load.

Due to the automated obstacle detection, it is now possible to use the autonomous overhead travelling crane in not barred areas where dynamic obstacles are expected.

7. EXPERIMENTAL RESULTS

In order to demonstrate the performance of the presented approach using ultrasonic sensors, different test runs have been performed in the Department of MRM of the University of Ulm. One of these test runs is presented in the following lines.

Fig. 12 depicts experimental results in a free corridor without any obstacle. Hence, the desired trajectory can be tracked without any modifications. The comparison of the desired and the actual load position points out the excellent tracking performance of the decentralized axis controller.

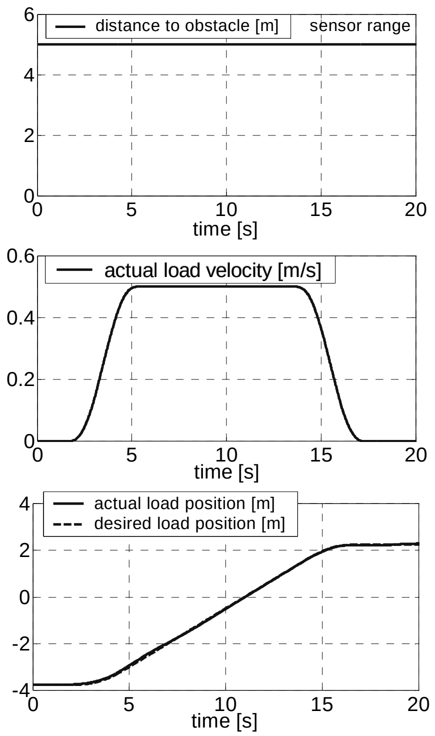

Fig. 12: Test run without any obstacles

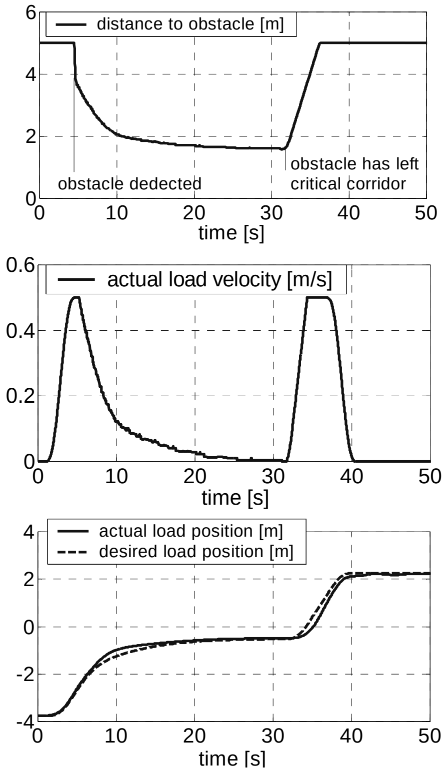

Fig. 13: Test run with obstacles

The second experiment shows the tracking of the same desired trajectory, but now with a dynamic obstacle moving in the corridor. As depicted in fig. 13, the obstacle is detected at t = 4.7 s by the ultrasonic sensors. As the distance falls below the limit value of 3.5 m at approximately 4.7 s, the desired velocity is reduced according to fig. 11, and accordingly the desired position, the desired velocity, the desired acceleration and the desired jerk. The load then stops at a distance of 1.2 m of the obstacle. When the obstacle moves out of the corridor at t = 31.7 s, the load can pursue the planned trajectory until it reaches the destination point. Despite the halt caused by the obstacle, the load oscillations of the load are successfully suppressed by the decentralized axis controller (fig. 13).

8. CONCLUSIONS

This paper presents an innovative approach to collision avoidance for rope-suspended material flow systems using three ultrasonic sensors. A 3D-map containing only static obstacles allows the calculation of an optimal path connecting the starting and destination points by means of a global path planning module. In order to obtain an autonomous material flow system, dynamic obstacles have to be taken into account. Hence, an observation of the path corridor is necessary to enable the use of the autonomous overhead travelling crane in not barred areas as well. The problems arising from the cross talk of the ultrasonic sensors have been solved by sequential triggering of the ultrasonic sensors. The presented experimental results demonstrate the successful integration of the collision avoidance module into the existing control structure of the overhead travelling crane. Current research concentrates on the detour strategy, i.e. autonomous detouring of detected dynamic obstacles.

REFERENCES

Aschemann, H., S. Lahres, O. Sawodny and E.P. Hofer (2000). *Gain Scheduled Motion Control of an Overhead Traveling Crane*, IFAC Conference on Control System Design, Bratislava, Slovak Republic, pp. 599 – 604

Aschemann, H. (2002). *Optimale Trajektorienplanung sowie modellgestützte Steuerung und Regelung für einen Brückenkran, Fortschritt-Berichte* (*in German*). Fortschrittberichte VDI, Reihe 8, Nr. 929, VDI Verlag, Düsseldorf,

Miyoshi, T. and K. Terashima (2004): *Position and Posture Control of Overhead Crane with Path Planning for Obstacle Avoidance*, CD-Proceedings of MOVIC 04, 5th International Conference on Motion and Vibration Control, St. Louis, USA

Wecker, T., H. Aschemann and E.P. Hofer (2003). *Autonomous Path Planning for an Overhead Travelling Crane*, ACE Workshop 2003, Duisburg, Germany, pp.89 – 94,