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VOLUME I

Session 1 - Systems Engineering and Intelligent Systems

Session 2 - Advances in Control Theory and Control Engineering

Session 3 - Optimisation and Management of Complex Systems and Networked Systems

Session 4 - Intelligent Vehicles and Mobile Systems

Session 5 - Robotics and Motion Systems

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Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Professor Peter Scharff
Rector, TU Ilmenau

Professor Christoph Ament
Head of Organisation

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T. Kopfstedt / J. W. Vervoorst

Formation Control for Groups of Mobile Robots Using a Hierarchical Controller Structure

1. INTRODUCTION

Nowadays most mobile robots are teleoperated or acting based on a preplanned mission plan as single individual robots. In the future more and more tasks will be done with robots and many of them require more autonomous functions of the robots and interaction between the robots. In future groups of robots will work together to fulfill missions such as humanitarian convoys, border patrol and search and rescue independently and reduce the risk for humans. In many of these missions a permanent communication between all members of the formation cannot be secured and is sometimes also not wanted, because intensive communication can be easily jammed or used for targeting on the formation in total or on single members of the formation of mobile robots. Accordingly a concept is presented which makes it possible for a group of mobile robots to fulfill a preplanned mission with limited inter-robot communication even in cases of unplanned changes of the trajectory for the group of mobile robots.
For such missions it is in most cases possible to generate a preplanned mission plan based on satellite maps, UAV data and digital maps. In this paper the mission plan for the group of mobile robots will be generated by Mixed Integer Programming as shown in [1] and [3]. This guarantees preplanned optimal trajectories for all members of the group of mobile robots. This information will be loaded into each robot a priori to the mission. During the mission the robots will follow this preplanned mission plan and, by the robots own onboard sensors, every robot will permanently measure the distance to the neighbors in the formation, to control and recalibrate the own position in the formation. The use of this concept enables a group of mobile robots to follow a preplanned optimal trajectory as a formation in a specified formation style without any communication if necessary.
In cases one robot of the formation of mobile robots detects an unknown obstacle it will activate its onboard fuzzy controller to avoid a possible collision with this obstacle. The other robots will detect the anomaly in the movement of this robot and automatically

react using their fuzzy controllers to try to keep in the predefined formation and, if this is impossible, to change the formation as long as necessary to surround the unknown obstacle and to return to the preplanned mission plan after that.
The following chapters will show the formulation of the MIP problem, the control structure, the design of the fuzzy controllers and simulation results for cases with a priori known and unknown obstacles.

2. HIERARCHICAL CONTROL STRUCTURE

The controller structure for the formation of mobile robots in this paper is divided into four control loops. These control loops represent different degrees of the level of control as shown in Fig. 1. In the Level 1 the complete mission is planned for each robot by several trajectory points which are connected by lines. Underneath this the fuzzy controller on each robot is implemented which is used during the movement of the robots along the trajectories to secure the formation stability and to avoid collisions with a priori unknown obstacles. The fuzzy controllers are also able to change the trajectories for the robots for passing around obstacles in a restricted area, but if greater changes should become necessary this must be done by the Level 1 using MIQP.

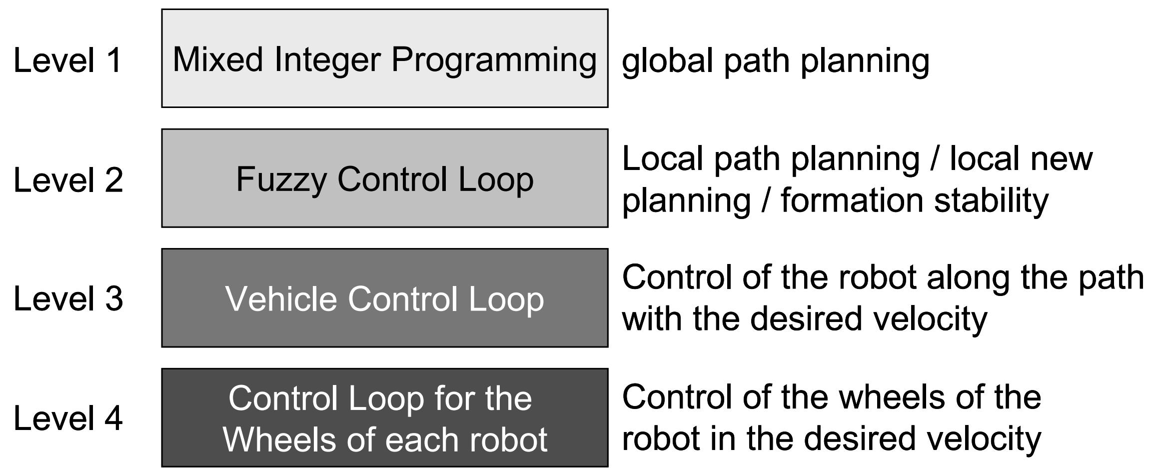

Figure 1: Hierarchical control structure

Beneath the fuzzy control loop each robot has a movement controller (Level 3) which generates the necessary command velocities for the wheels of the robot. As each wheel of the robot has is independently actuated the lowest level of the controller architecture is represented by the motor controller (Level 4) for each wheel of the robot.

3. MIXED INTEGER PROGRAMMING

The equations for the MIP problem which must be solved to generate the optimal trajectories for the formation of mobile robots can be described using [1], and [2]. The dynamic model for a mobile robot can be described according to [1] as

$$(1)\qquad \frac{d}{dt}\begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -gc_2 - \frac{\mu}{m} & 0 \\ 0 & 0 & 0 & -gc_2 - \frac{\mu}{m} \end{bmatrix} \begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{m} & 0 \\ 0 & \frac{1}{m} \end{bmatrix} \begin{bmatrix} f_x \\ f_y \end{bmatrix}$$

where m is the mass of the robot, f_x and f_y are the forces from the engine of the robot and $gc_2 + \mu$ are constants to describe the friction effect for rolling over ground and the mechanical parts around the engine in the robot as explained in [1]. The connection between the robots j and $j+1$ can be described according to [3] as

$$(2)\qquad \begin{aligned} x_{t,j+1} - x_{t,j} &= x_{dist,j} \\ y_{t,j+1} - y_{t,j} &= y_{dist,j} \end{aligned}$$

in which $x_{dist,j}$ and $y_{dist,j}$ are static values for the description of the distance between two robots. This must be done for all connections between the robots in the formation to describe a complete formation. As shown in [1] alternative algorithms with more complex structures will also allow the description of variable formations and formation switching. In addition to the robot description and the description of the links between the robots also the obstacles must be described in a way as shown in [3] by using the system of equations:

$$(3)\qquad \begin{aligned} x_{t,j} - S\cdot\varepsilon_1 &\le x_{\min} \\ -x_{t,j} - S\cdot\varepsilon_2 &\le -x_{\max} \\ y_{t,j} - S\cdot\varepsilon_3 &\le y_{\min} \\ -y_{t,j} - S\cdot\varepsilon_4 &\le -y_{\min} \\ \sum_{i=1}^{4}\varepsilon_i &\le 3 \end{aligned}$$

with S as a large positive number, the lower left edge $x_{\min}, y_{\min}$ and the upper right edge $x_{\max}, y_{\max}$ of the obstacle and $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4$ as Boolean variables.

Further methods to describe of more complex obstacles which partially have already been tested with the algorithms shown in this paper, are described in [4] and [5].

The optimization problem itself can be described by the minimization criterion

(4) $$\min_{\Delta s} \sum_{t=1}^{T-1} \sum_{j=1}^{M} \Delta s_{t,j}$$

Subject to $$\begin{bmatrix} \text{MLD system representation of (1)} \\ (2) \\ (3) \\ s_{T,j} = s_{goal,j} \end{bmatrix}$$

where $\Delta s_{t,j} = s_{t,j} - s_{t-1,j}$ is the difference in the position $s_{t,j} = [x_{t,j}, y_{t,j}]^T$ between two steps of a robot, and $s_{T,j} = s_{goal,j}$ is the reaching goal criteria to ensure that in the last step of the trajectory each robot reaches its own target point. This minimization problem can be solved by any MIQP solver and the result is the optimal trajectory through the scenario for the formation of mobile robots.

4. FUZZY CONTROL

The architecture of the fuzzy controller is an extension of the work from [4] and is based on [6] for the obstacle avoidance. As described in the hierarchical control structure part of this paper the fuzzy controller is permanently controlling the distances to the other robots to ensure that all robots keep in formation.

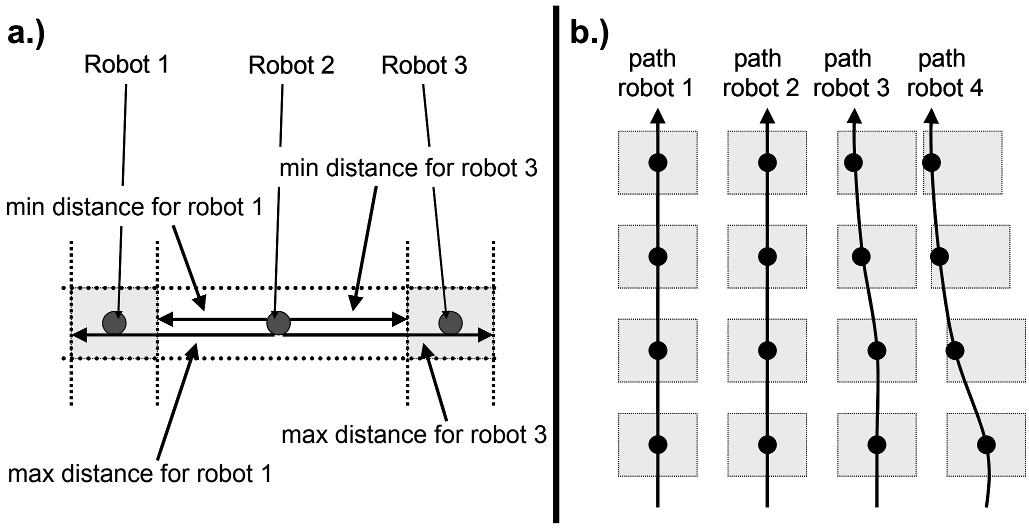

Figure 2: a) allowed robot positions b) collision avoidance

Therefore, as shown in Fig. 2a, each robot only controls the distances to its neighbors. If one of the robots has to change its position in a way that the formation stability is no longer guaranteed the neighboring robots will also change their positions as long as necessary to regain a stable formation. This is shown in Fig. 2b.

5. SIMULATION

Based on the information from Fig. 3a the trajectories in Fig. 3b are generated using MIQP for the formation of mobile robots. As all obstacles have been known during the planning phase of the mission (Level 1 in the hierarchical control structure) the solution for each robot is the optimal path through the scenario.

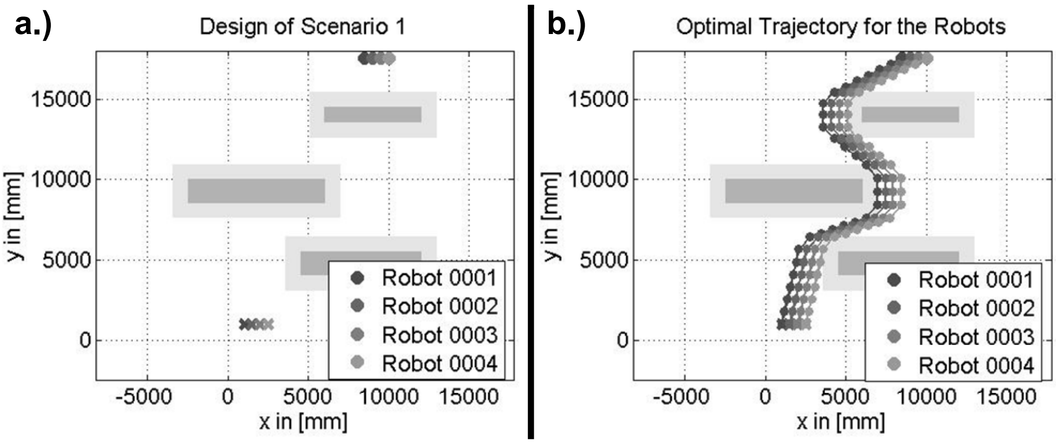

Figure 3: Scenario 1, all obstacles are known

In difference to the scenario shown in Fig. 3 the scenario in Fig. 4a is not known in total during the planning phase of the mission. The obstacle marked "unknown" is unknown during the planning phase of the mission. The result is that the trajectories from the MIQP are going through the unknown obstacle as shown in Fig. 4b. During the mission this obstacle will be detected by the sensors of one of the robots from the formation of mobile robots. At this moment the Fuzzy Controller of the robot No. four starts to change the trajectory for this robot. This is detected by robot No. three and this robot also changes its own trajectory a bit. The robots No. one and No. two are able to follow the preplanned trajectory.

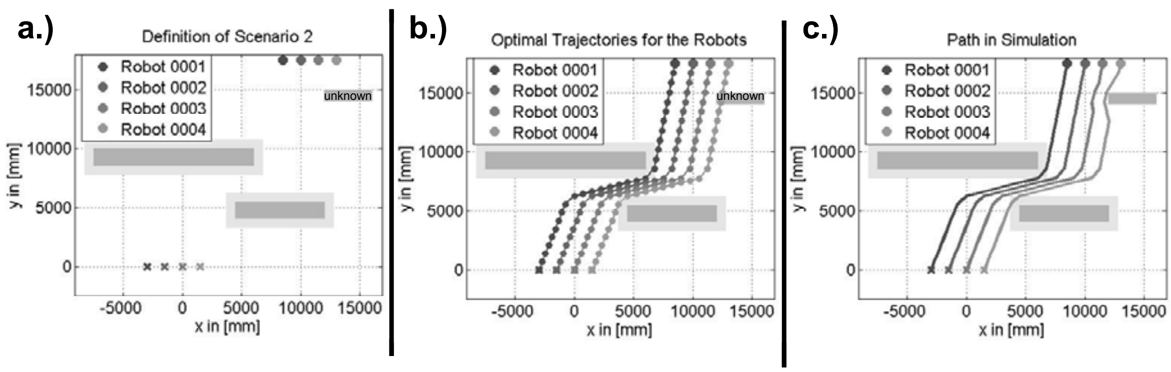

Figure 4: Scenario 2, working with unknown obstacles

Behind the unknown obstacle the robots No. three and No. four return to their preplanned trajectories and the mission continues using the preplanned trajectories for all robots. If the robots would have been unable to return to their trajectories or if all robots would have moved to a big distance from the preplanned trajectories a new planning of the trajectories for all robot using the MIQP would have taken place. If such new planning becomes necessary the robots have to communicate with each other to update their scenario information and resulting trajectories from the MIQP. In the other cases, as it is shown here in Fig. 4c, the robots do not need to communicate with each other during the mission as all necessary information about the other robots of the formation can be gathered by the onboard sensors of each robot.

6. CONCLUSION

As shown in Fig. 3 and Fig. 4 the hierarchical controller structure which is presented in this paper works with formations of four robots for scenarios in which all information is a priori known as well as for such scenarios in which some obstacles are unknown during the planning phase of the mission or in which the scenario changes during the mission. If all data are known before the mission starts the optimal path is found. In the other case only one possible path could be found due to the limited information available.

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