Control of Autonomous Robots in the RoboCup Scenario using Coupled Selection Equations

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1 Introduction

Concepts of self–organization, adapted from physics, chemistry or biology [1], [2], [3] are more and more important for the implementation of suitable control mechanisms in the field of artificial intelligent systems and especially in the field of distributed autonomous mobile robotic systems. These concepts seem to be very promising to guarantee the required flexibility, robustness and fault–tolerance.

For the control of autonomous robots in the RoboCup scenario* a dynamical system approach is used. This control method consists of an assignment algorithm based on pattern formation principles and a collision avoidance algorithm based on a behavioral force model [4], [5].

The first part, the algorithm based on pattern formation principles, is adapted from physics capable to solve an important subclass of combinatorial optimization problems, namely the so-called assignment problems [6], which occur often in flexible manufacturing systems and other operational areas. Due to the inherent self–organization process, this algorithm ensures fault–tolerant behavior.

In the case of the two-index assignment problem treated here elements of two sets have to be assigned in such a way that each element of set one is assigned to one and only one element of set two and vice versa. Hereby a given linear objective function has to be minimized. In the RoboCup scenario the elements could be for instance targets (T) like the ball, an opponent, or a special position in the field and the robots of the own soccer team.

In [7] and [8] the information about all obstacles is based on communicated information. So each obstacle is just represented through the coordinates and a given diameter. Now we just use the information of the robot sensors. So each obstacle is not any longer represented by a single point but the shape recognized by the robot. For obstacle detection we use a SICK Laser Range Finder†.

* http://www.robocup.org

† Thanks to the SICK AG (http://www.sick.de) for lending us some Laser Range Finders.

2 Description of the Control Method

As mentioned before, the task to be solved is the assignment of autonomous mobile robots to fixed targets such that every target is served by exactly one robot. The proposed mechanism consists of mainly two ideas: The first idea is to use a specific behavioral force model¶ for the navigation which controls the velocities $v_i(t) \in \mathbb{R}^2$ of the robots respectively [10]. The second idea is to solve the underlying assignment problem using coupled selection equations [11]. The appropriate combination of both ideas avoids collisions with obstacles and other robots on the one hand and guarantees a unique, always feasible and flexible (due to the self-organization process) assignment on the other hand.

2.1 Equation of Motion

The equation of motion for the velocity $\boldsymbol{v}_i(t)$ of the robot i with $i \in \{1, \cdots, n\}$, with totally n robots, is according to [4] and [8]:

$$\dot{\boldsymbol{v}}_i(t) = \frac{1}{\tau}\left(v_i^0 \boldsymbol{e}_i(t) - \boldsymbol{v}_i(t)\right) + \sum_{i' \neq i} \boldsymbol{f}_{ii'}\left(\boldsymbol{r}_{i'}(t) - \boldsymbol{r}_i(t)\right) + \sum_k \boldsymbol{f}_{ik}\left(\boldsymbol{x}_k - \boldsymbol{r}_i(t)\right) \quad (1)$$

Hereby, the two summations have to be taken over the number of robots at the positions $\boldsymbol{r}_{i'}(t)$ and of obstacles located at $\boldsymbol{x}_k$ which may be present in the working space of the robots.

We modified equation (1) in such a way, that the sensor information about the distance to the other robots $\boldsymbol{r}_{i'}(t)$ and the obstacles $\boldsymbol{x}_k$ in each detected direction is directly used for the repelling force. In the implementation of equation (1) used in [8] also the boundaries of the experimental area are ignored. Now we just use the information which is provided directly by the SICK Laser Range Finder used by the robots. As shown in Figure 1 the repelling force yields distances to the nearest obstacle or robot for the front 180° with an angular resolution of 1°. Hence the new equation of motion is:

$$\dot{\boldsymbol{v}}_i(t) = \frac{1}{\tau}\left(v_i^0 \boldsymbol{e}_i(t) - \boldsymbol{v}_i(t)\right) + \sum_{k=0}^{180} \boldsymbol{f}\left(\boldsymbol{\rho}_k(t)\right) \quad (2)$$

The parameter τ, the so called relaxation time, is a measure how fast the actual velocity $\boldsymbol{v}_i(t)$ tends towards the intended velocity $v_i^0 \boldsymbol{e}_i(t)$. The parameter $v_i^0 \in \mathbb{R}$ is the appropriate working speed of the robot i. The normalized vector $\boldsymbol{e}_i(t) \in \mathbb{R}^2$ represents the direction which is assigned to the corresponding robot i by the coupled selection equation described below. For each direction k of the laser beam the distance vector $\boldsymbol{\rho}_k(t)$ of the nearest obstacle or robot is measured (see Figure 1) and used for the repulsive force $\boldsymbol{f}$. The repulsive force $\boldsymbol{f}$ of the robot is caused by approaching an obstacle or another robot.

¶ see, e.g., [9] for an overview

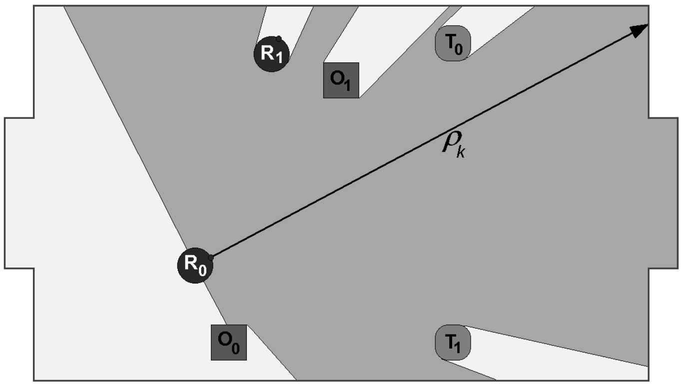

Fig. 1. *Measurement of the front 180° distances of the robot R_0 using its Sick Laser Range Finder. The dark area is covered by the laser beam. One beam, which is measuring the distance vector $\boldsymbol{\rho}_k(t)$, is shown. The other robot is marked with R_1, the obstacles with O_0 and O_1 and the two targets with T_0 and T_1.*

2.2 Collision Avoidance.

To ensure collision avoidance, a behavioral force model is used. Therefore, the short range force field $\boldsymbol{f}\left(\boldsymbol{\rho}_k(t)\right)$ is introduced (see [4]) in the equation of motion (2). The repulsive force acting on a specific robot caused by adjacent obstacles is defined by:

$$\boldsymbol{f}(\boldsymbol{\rho}) = \begin{cases} \eta\left(\tan h(\tilde{\rho}) - h(\tilde{\rho})\right) \frac{\boldsymbol{\rho}}{\|\boldsymbol{\rho}\|} & \text{for } 0 < \tilde{\rho} \leq \sigma \\ 0 & \text{for } \tilde{\rho} > \sigma \end{cases} \tag{3}$$

with $\tilde{\rho} = \|\boldsymbol{\rho}\| - d^R$ and $h(\tilde{\rho}) = \frac{\pi}{2}(\frac{\tilde{\rho}}{\sigma} - 1)$, where $\tilde{\rho}$ describing the distance between the robot and the obstacles detected by the laser and $\|\cdot\|$ is the Euclidean norm. Hereby d^R is the distance between the laser scanner and the robot's surface. The parameter η is used to adapt the force $\boldsymbol{f}$ to an appropriate repelling strength. The used force, specified in equation (3), is, though piecewise defined, continuous and differentiable and is identical to zero if the distance between two objects is larger than the appropriate chosen range parameter σ. If large enough distances between the obstacles are assumed, this property avoids unwanted stable points of the dynamical system (2) which could trap the robots and cause the system to fail. This is in contrast to the usually observed trapping behavior of most other approaches which is reported e.g. in [9].

2.3 Dynamic Selection of Targets.

In the equation of motion (2) the destination vector $\boldsymbol{e}_i(t)$ determines the intended moving direction of the robot i [4]. It is defined by a kind of linear combination of the difference vectors of the robot positions $\boldsymbol{r}_i(t)$ and all target positions $\boldsymbol{g}_j$

with $j \in \{1, \cdots, n\}$ and n is equal to number of used robots.

$$\boldsymbol{e}_i(t) = \boldsymbol{\Phi}_{\gamma,\delta} \left(\sum_j \xi_{ij}(t) \boldsymbol{\Phi}_{\gamma,\delta} \left(\boldsymbol{g}_j - \boldsymbol{r}_i \right) \right) \tag{4}$$

The function $\boldsymbol{\Phi}_{\gamma,\delta}(\boldsymbol{y}) = \frac{\boldsymbol{y}}{\|\boldsymbol{y}\|+1/(\gamma\|\boldsymbol{y}\|+\delta)}$ with $\gamma, \delta > 0$ mainly normalizes the vector $\boldsymbol{y}$ and avoids a singularity at $\boldsymbol{y} = \boldsymbol{0}$. The time dependent coefficient $\sum_j \xi_{ij}(t)$ dynamically selects the target for each of the robots. To ensure that each robot selects one and only one target and every target is served by one and only one robot, the following coupled selection equations [11] are used:

$$\dot{\xi}_{ij} = \kappa \xi_{ij} \left(1 + (2\beta - 1)\xi_{ij}^2 - \beta \left(\sum_{i'} \xi_{i'j}^2 + \sum_{j'} \xi_{ij'}^2 \right) \right) \tag{5}$$

The parameter κ is needed to adjust the time-scales between the processes of navigation (2) and assignment (5). The coupling is controlled by β, with $\beta > \frac{1}{2}$. For the initial values $\xi_{ij}(t)$ the sum of the Euclidean distances d_{ij} of the initial positions $\boldsymbol{r}_i(0)$ of the robots to the targets at the locations $\boldsymbol{g}_j$ are used:

$$\xi_{ij}(0) = 1 - \frac{d_{ij}}{d_{max}} \tag{6}$$

with $d_{max} \geq \max_{i',j'} (d_{i'j'})$ and $d_{ij} = \|\boldsymbol{r}_i(0) - \boldsymbol{g}_j\|$.

3 Results

The suggested control method was verified by computer simulations. The task was the assignment and movement of the robots to targets. In the RoboCup scenario the targets could be the ball, the goal, free space or an opponent. This was done in such a way that each target was served by exactly one robot. Furthermore the robots have to avoid collisions with randomly placed obstacles, in case of RoboCup the opponents or other team members.

The main goal of replacing the old equation of motion (1) through the new one (2) was to use the information provided by the laser range finder. Due to this the surrounding walls are not longer unattended. In Figure 2 the trajectories are shown, where two robots moving from the left to the targets in the right. The robots have been controlled with the equation of motion (1), without the adaption to the laser range finder. In contrast to that in Figure 3 the equation of motion (2) was used for solving the same task. Due to the adapted equation of motion (2) the surrounding wall is inherently recognized.

The assignment of the robots to the targets is one central task of the presented control method. In Figure 4 four robots are assigned and move to four targets. Due to the late assignment the robots first move towards the main focus of the targets. This is well to see in the right (robot 2 and 3). During the movement of

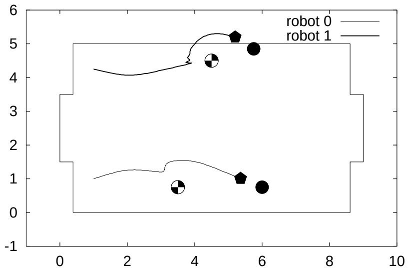

Fig. 2. *Trajectories of the two simulated robots using equation (1). No information about the surrounding wall is present.*

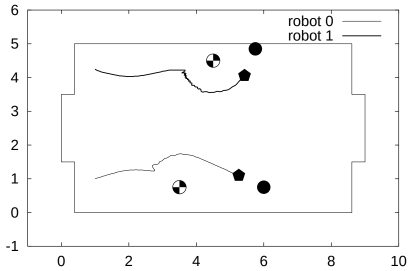

Fig. 3. *Trajectories of the two simulated robots using equation (2). The information about the obstacles and the surrounding wall is provided by the laser range finder.*

the robots collision avoidance was successfully done by the behavior-based force model of equation (2) with the specific force terms defined in equation (3). In Figure 3 one can clearly see the effect of the repulsive forces of the obstacles and the boundaries of the soccer field. In terms of the potential field, it is clear, that the repelling force determined by eq. (2) leads to a much more detailed potential landscape than the traditional approach [12] where the obstacles are modeled by circumscribed rectangles or circles.

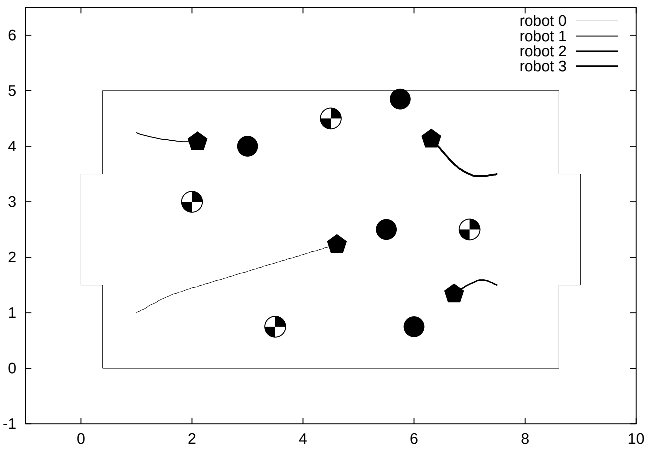

Fig. 4. *Trajectories of 4 robots moving to the assigned targets*

In Figures 5 – 8 the time evolutions of the elements ξ_{ij} of the ξ-matrix demonstrating the competition process of the assignment is shown. Figure 5 shows the relevant row of the ξ-matrix of robot 0, Figure 6 of robot 1 and so on. One can see, that finally each target is served by exactly one robot as required for the task the robots have to perform.

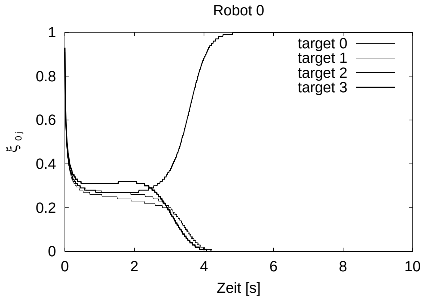

Fig. 5. *ξ-dynamic of robot 0. It is assigned to target 2.*

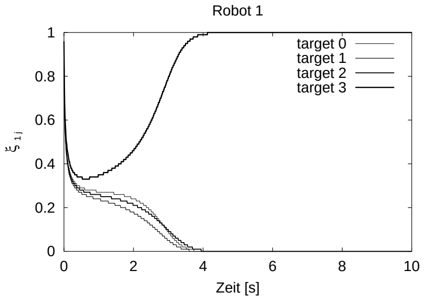

Fig. 6. *ξ-dynamic of robot 1. It is assigned to target 3.*

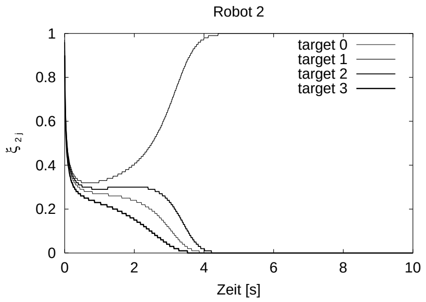

Fig. 7. *ξ-dynamic of robot 2. It is assigned to target 1.*

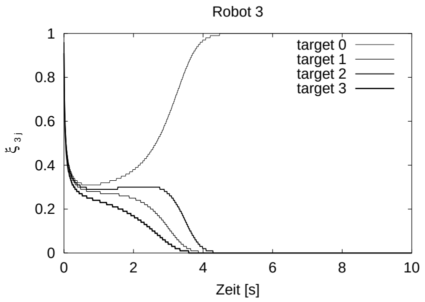

Fig. 8. *ξ-dynamic of robot 3. It is assigned to target 0.*

4 Conclusion and Outlook

The results show that the presented control method for a complex robot to target assignment scenario, which is in principle applicable in the RoboCup scenario, works very well. Using this method, self-organizing behavior of the autonomous mobile robots can be achieved in engineering applications.

In future work parameter studies are planned to investigate and improve the behavior systematically. For instance it is necessary for the calculation of the total repelling force in eq. (2) to distinguish between forces caused by the static boundaries of the soccer field and by dynamic objects. In particular one has to adjust the parameters η and σ to cope with these two different cases.

Furthermore some specific situations which could appear in RoboCup scenarios will be considered. One may think of the selection between several offense and defense patterns of the robots realizing self-organized group behavior.

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