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COORDINATED TRANSPORTATION WITH MINIMAL EXPLICIT COMMUNICATION BETWEEN ROBOTS [1]

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Abstract: We propose and demonstrate how attractor dynamics can be used to design and implement a distributed dynamic control architecture that enables a team of two robots, without force/torque sensors and equipped solely with low-level sensors, to carry a long object and simultaneously avoid obstacles. The explicit required communication between robots is minimal. The robots have no prior knowledge of their environment. Experimental results in indoor environments show that if parameter values are chosen within reasonable ranges then the overall system works quite well even in cluttered environments. The robots' behavior is stable and the generated trajectories are smooth.

Keywords: mobile robots, object transportation, collision avoidance, attractor dynamics.

1. INTRODUCTION

The challenge to develop autonomous robots able to transport large size objects in cooperation with other robots or humans (see Figure 1) is an important endeavor since such robots would be very useful in many fields related to our daily activities, such as in construction sites, at home, at office or at industrial plants. Thus, many researchers concentrate their efforts in the development of such robotic systems (e.g. Arai and Ota (1997),Ahmadabadi and Nakano (2001),Takeda *et al.* (2003)).

Fig. 1. Object transportation task. **Left**: human-robot team **Right**: Robot-Robot team.

Here we focus on the problem of controlling and coordinating two tracked non-holonomic mobile robots that must carry a large size object in an unknown environment, equipped solely with low-level sensors, and without force/torque sensors. Particular to our approach, we use non-linear dynamical systems as a design and theoretical tool to design and implement a distributed control architecture that controls the behavior

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of each robot. Specifically, the time course of the control variables (i.e. heading direction and path velocity) are obtained from (constant) solutions of dynamical systems. The attractor solutions (asymptotically stable states) dominate these solutions by design. Our motivation comes from previous studies (Schöner *et al.*, 1995; Bicho and Schöner, 1997; Steinhage, 1998; Large *et al.*, 1999; Bicho *et al.*, 2000; Althaus *et al.*, 2001) on single robots systems which have shown that these theoretical and design tools can be used to describe the dynamic coupling between the robot and its environment. An open questions is what is the extend to which these same tools can be used to control the behavior of robots that are tightly coupled and must work as a team. We hope the work reported here is a step toward an answer, i.e. pushing forward this *dynamic approach to robotics* into the domain of multi-robot systems.

This paper builds on previous work reported in (Bicho *et al.*, 2003) [4]. There we have proposed a control architecture, completely formalized and implemented as a non-linear dynamical system, that controls the behavior of an autonomous mobile robot that must transport a large size object in cooperation with a human (left panel in Figure 1). Here we extend that previous work and demonstrate how it lends itself naturally to the scenario where the partner agent is a robot instead of a human (i.e. right panel in Figure 1).

We assume that the robots have no prior knowledge of the environment and we choose a *leader-follower* decentralized motion control strategy as in (Takeda *et al.*, 2003). The *leader* robot (i.e. the robot that has replaced the human) drives from an initial position to a final target destination. The other robot (i.e. *follower/helper*) takes the *leader robot* as a reference point, and must steer so as to keep at all times the correct orientation and distance that permits it to cooperate in the transportation task and simultaneously avoid any obstacles (static or dynamic) that may appear.

In our approach the control architecture of each robot is structured in terms of elementary behaviors. The individual behaviors and their integration are generated by non-linear dynamical system and we use bifurcation theory to make design decisions around points at which sensory and/or communicated information must induce a switch from one type of solution to another. The benefit is that the mathematical properties associated with the concepts (c.f. Section 3) enable system integration including stability of the overall behavior of the autonomous systems.

The rest of the paper is structured as follows: next section presents the robots and their basic capabilities. In Section 3 we define and describe the behavioral dynamics for each robot in the team. Implementation details and results obtained from real experiments are presented in Section 4. The paper ends with Section 5 with a brief discussion, conclusions and an outlook for future work.

2. ROBOTS DESCRIPTION AND CAPABILITIES

The control and coordination of the two robots (see Figure 2) is based on the following ideas: ***i)*** The *leader* robot holds an extremity of the object and moves from an initial position to a final destination. ***ii)*** The *follower* robot must "help" the *leader* to carry the long object by steering so as to keep at all times the orientation and distance to the *leader*. By default the robots must transport the object as illustrated in the right panel of Figure 1, i.e. one following behind the other. ***iii)*** The robots must be able to avoid collisions with sensed obstacles. ***iv)*** Each robot has a free rotational joint coupled to a free prismatic joint. These are used to support the object and provide important information to the robots (see Figure 2): ***a)*** from the current angle of the free rotational joint the *follower* knows the direction, ψ_{leader}, at which the *leader* is as seen from its current position and with respect to the external reference axis x; ***b)*** displacements (Δd) measured in the free prismatic joint are used by the *follower* to control its distance to the *leader*. If Δd increases above 15 cm the object falls down since it is not fixed to the prismatic joint.

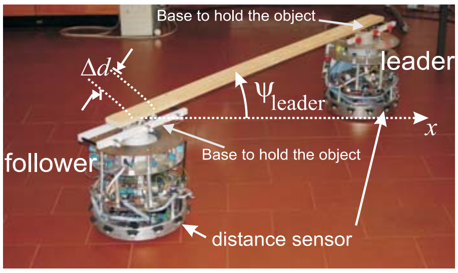

Fig. 2. Each robot has a base on the top of which one extremity of the object is placed. Each base consists of rotary joint coupled to a prismatic free joint. The first permits to measure the angle ψ_{leader} and the second displacements (Δd) of the bar. Each platform has a single board computer system based on a 586DX4 processor operating at 133 MHz, equipped with 4 Mbytes of DRAM and 8 Mbytes of FLASH memory. All programming, control and computation are done on-board. The two lateral wheels are each driven by a DC brushless servo-motor. Each robot is equipped with nine infra-red sensors, which are used to measure distance to obstructions at the directions at which they are pointing in space. The angular range over which distances are averaged is about 30 deg. The distance range was set to 80 cm.

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[4] see videos in http://www.dei.uminho.pt/pessoas/estela/

3. ATTRACTOR DYNAMICS FOR OBJECT TRANSPORTATION

To model the robots' behavior we use their *heading direction*, ϕ ($0 \leq \phi \leq 2\pi$ rad), with respect to an arbitrary but fixed world axis[5], and *path velocity*, v. Behavior is generated by continuously providing values to these variables, which control the robot's wheels. The time course of each of these variables is obtained from (constant) solutions of dynamical systems. The attractor solutions (asymptotically stable states) dominate these solutions by design. In the present system, the *behavioral dynamics* of heading direction, $\phi_r(t)$, and velocity, $v_r(t)$,($r =$ leader, follower) are differential equations

$$\dot{\phi}_r = f_r(\phi_r, \text{parameters}) \qquad (1)$$
$$\dot{v}_r = g_r(v_r, \text{parameters}). \qquad (2)$$

Task constraints define contributions to the vector fields, $f_r(\phi_r, \text{parameters})$ and $g_r(v_r, \text{parameters})$. The *leader*'s *heading direction* dynamics has been previously defined and evaluated (see (Bicho *et al.*, 2000)). Next, we build the *follower*'s *heading direction* dynamics. In subsection 3.2 we derive, for both robots, the vector fields for the velocity control dynamics.

3.1 Attractor dynamics for the follower's heading direction

In the absence of sensed obstacles the *follower* robot helps the *leader* by following behind it. We say that the *follower* drives in column formation with the *leader*, if it drives behind it at a desired distance. As illustrated in Figure 2, the direction ψ_{leader}, in which the leader is "seen" from the current position of the *follower* specifies a desired value for its heading direction. A simple dynamical system for the robot's heading direction that generates navigation in column formation taking the *leader* as a reference point is

$$\dot{\phi} = f_{\text{col}}(\phi) = -\lambda_{\text{col}} sin(\phi - \psi_{\text{leader}}) \qquad (3)$$

which erects an attractor for ϕ directly at the direction ψ_{header}) (see Figure 3).

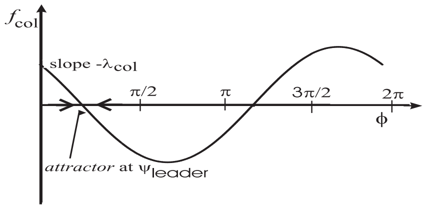

Fig. 3. The direction $\phi = \psi_{\text{leader}}$ is a fixed point attractor ($\dot{\phi} = 0$ there with negative slop) with strength λ_{col}. This vector field behaves as an attractive force that attracts ϕ to the value ψ_{leader}. Because orientation toward ψ_{leader} is desired from any starting orientation of the *follower* robot, the range over which this attractor exerts its attractive effect is the entire full circle. As a consequence there is a repeller at the back, in the direction opposite to that toward the *leader*.

3.1.1. Integration with obstacle avoidance: An obstacle avoidance dynamics formulated at the level of heading direction, when the robot moves without the constraint to help carrying the object, has been previously elaborated and implemented on the vehicle platform (details may be found in Bicho and Schöner, 1997; Bicho, 2000; Bicho *et al.*,2000)

$$\dot{\phi} = \sum_i f_{\text{obs},i}(\phi) \qquad (4)$$

where each

$$f_{\text{obs},i} = \lambda_{\text{obs},i}(\phi - \psi_{\text{obs},i}) \exp\left[-\frac{(\phi - \psi_{\text{obs},i})^2}{2\sigma_i^2}\right] \qquad (5)$$

is a repulsive force-let (see Figure 4) erected by distance sensor i when it detects an obstruction. $\psi_{obs,i}$ is the direction in the world in which sensor i is pointing. Sensor i is mounted at an angular position θ_i with respect to the robot's heading direction. Because ϕ, is defined relative to the same reference frame, the relevant difference, $\phi - \psi_{\text{obs},i} = -\theta_i$ is actually a constant. This illustrates that the calibration of the robot's heading direction in the world is irrelevant. The strength of repulsion, $\lambda_{\text{obs},i}$, of each contribution is a decreasing function of the sensed distance:

$$\lambda_{\text{obs},i} = \beta_1 \exp\left[-d_i/\beta_2\right] \qquad (6)$$

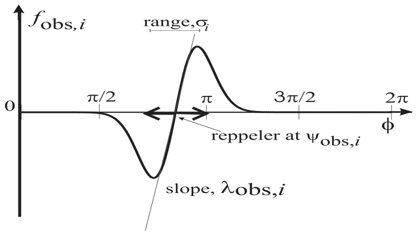

Fig. 4. A contribution to the dynamics of heading direction expressing the task constraint "avoid direction of the obstacle" is a force-let with a fixed point reppeler (zero with positive slope) at the direction, $\psi_{\text{obs},i}$ at which an obstruction has been detected. Every distance sensor ($i = 1, 2, \ldots$) contributes with such a force-let centered on the direction in which the sensor points. By decreasing the slope ($\lambda_{\text{obs},i}$) with increasing measured distance, only nearby surfaces repel strongly. The range of the force-let (σ_i) is limited based on sensor range and on the constraint of passing without contact.

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[5] the external reference frame does not need to be the same for both robots

which depends on two parameters controlling overall strength (β_1) and spatial rate of decay (β_2). The angular range,

$$\sigma_i = \arctan\left[\tan(\frac{\Delta\theta}{2}) + \frac{R_{\text{robot}}}{R_{\text{robot}} + d_i}\right] \tag{7}$$

over which the contribution exerts its repulsive effect is adjusted taking both sensor sector, $\Delta\theta$, and the minimal passing distance of the vehicle (at size R_{robot} of the platform) into account.

With the constraint to help the *leader* robot to carry the object without letting it fall down, this obstacle avoidance dynamics can not be used directly to control the *follower*'s heading direction dynamics. However, it can be used to compute the desired value for the *follower*'s heading direction when this robot senses obstructions while transporting the object in cooperation with the *leader*.

When moving around an obstacle the desired value for the *follower*'s heading direction is $\psi_{\text{leader}} + \Delta\psi_{\text{obs}}$[6] if the obstacle is to the right or $\psi_{\text{leader}} - \Delta\psi_{\text{obs}}$ if the obstacle is to the left. An adequate and simple dynamical system that generates the time course for the heading direction of this robot during the obstacle avoidance reads

$$\dot{\phi} = f_{\text{obs}}(\phi) = -\lambda_{\text{obs}} sin(\phi - \psi_{\text{des}}) \tag{8}$$

which erects an attractor at

$$\psi_{\text{des}} = \psi_{\text{leader}} + \alpha_{\text{obs}}\Delta\psi_{\text{obs}} \tag{9}$$

with fixed strength of attraction (i.e. relaxation rate) λ_{obs}. α_{obs} reads:

$$\alpha_{\text{obs}}(\phi) = \begin{cases} -1 & \text{for } \sum_i f_{\text{obs},i}(\phi) < 0 \\ 1 & \text{else} \end{cases}. \tag{10}$$

This function that takes the value -1 if the *follower* robot detects obstructions on its left side or is equal to 1 if obstructions are to the right.

The complete behavioral dynamics of the *follower*'s heading direction is governed by:

$$\dot{\phi} = \gamma_{\text{col}} f_{\text{col}}(\phi) + \gamma_{\text{obs}} f_{\text{obs}}(\phi) + f_{\text{stoch}}. \tag{11}$$

Where γ_{col} and γ_{obs} are mutually exclusive activation variables that, depending on the sensorial information acquired by the distance sensors mounted on the robot determine which component term of the vector field must dominate the dynamics. In the absence of obstacles the term f_{col} must dominate the vector field, so $\gamma_{\text{col}} = 1$ and $\gamma_{\text{obs}} = 0$ is required. Conversely, when obstructions are detected $\gamma_{\text{col}} = 0$ and $\gamma_{\text{obs}} = 1$ is desired. See (Bicho *et al.*, 2003) for how to compute these variables' activation from the potential function of the virtual obstacle avoidance dynamics defined by Eq. 4.

f_{stoch} is a stochastic force that ensures escape from reppelers within a limited time. The heading direction might fall in a reppeler when due to a bifurcation in the dynamics the attractor, in which the heading direction sits, becomes a reppeler.

One very important and useful remark is that the complete behavioral dynamics for the heading direction (i.e. Eq. 11) does not depend on the calibration of the *follower*'s heading direction. There are two reasons for this: ***i)*** The right hand side of the virtual obstacle avoidance dynamics (Eq. 4) does not actually depends on the heading direction because $\phi - \psi_{\text{obs},i} = -\theta_i$ is actually a constant. It only depends on the distance measures given by the distance sensors. The same is concomitantly true for α_{obs} and the activation variables γ_{col} and γ_{obs}. ***ii)*** The terms f_{col} and f_{obs}, given by Eq. 3 and Eq. 8 respectively, depend only on the difference $\phi - \psi_{\text{leader}}$ ($= \Delta\psi$) which can be directly read by the sensor mounted on the rotational joint (see Figure 2).

3.2 Velocity control dynamics

3.2.1. Follower's path velocity: The *follower*'s path velocity must be controlled so that this robot keeps the desired distance to the *leader* at all times. A necessary condition to help the *leader* to carry the object with success. At each instant in time the *follower*'s required path velocity depends on the path velocity of the *leader* (i.e. $v_{\text{leader}}(t)$) and on the constraint to drive at a fixed distance from the *leader*. This can be accomplished by controlling the *follower*'s path velocity, v_{follower}, by means of a dynamical system

$$\dot{v}_{\text{follower}} = \gamma_{\text{col}} g_{\text{col}}(v_{\text{follower}}) + \gamma_{\text{obs}} g_{\text{obs}}(v_{\text{follower}}) \tag{12}$$

where each contribution to the vector field is a linear force-let(i =col,obs)

$$g_i = -c_i(v - v_{\text{d},i}) \tag{13}$$

that erects an attractor at the required velocity, $v_{\text{d},i}$, with strength, c_i:

$$v_{\text{d,col}} = \begin{cases} -v_{\text{leader}} + \Delta d/T_{2c} & \\ & \text{for } \Delta d < 0 \\ v_{\text{leader}} + \Delta d/T_{2c} & \text{else} \end{cases} \tag{14}$$

$$v_{\text{d,obs}} = \begin{cases} -v_{\text{leader}} + \Delta d/T_{2c} - \kappa|\cos(\psi_{\text{leader}})| \\ \qquad \text{for } \Delta d < 0 \\ v_{\text{leader}} + \Delta d/T_{2c} - \kappa|\cos(\psi_{\text{leader}})| \\ \qquad \text{else} \end{cases} \tag{15}$$

3.2.2. Leader's path velocity: As this robot moves its sensory information changes and thus

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[6] $\Delta\psi_{\text{obs}}$ is a fixed parameter equal to $\pi/4$.

attractors (and repellers) shift. Since its the heading direction must be in or near an attractor at all times, for the design principle to work, we must limit the rate of such shifts to permit the *leader*'s heading direction to track the attractor as it moves and thus stay close to a stable state. Additionally, for better team performance its desired path velocity should be also constraint by the transportation task. The *leader*'s path velocity can be controlled by means of a simple linear dynamical system that imposes an attractor at the desired path velocity:

$$v_{\mathrm{d,l}} = \begin{cases} d_{\mathrm{obs}/T_{2\mathrm{c}}} & \text{, if } U_{\mathrm{obs}}(\phi_{\mathrm{leader}}) > 0 \bigwedge \Delta d < 5 \\ 10 & \text{, if } U_{\mathrm{obs}}(\phi_{\mathrm{leader}}) \leq 0 \bigwedge \Delta d < 5 \\ 5 & \Delta d > 5 \end{cases} \tag{16}$$

with relaxation rate c. Here U_{obs} is the potential function of its obstacle avoidance dynamics (see (Bicho *et al.*, 2000) for details) and Δd is communicated by the *follower* robot.

Note that in case the *leader* robot has a sensor on its prismatic joint (as is the case for the *follower*) there is no need that the follower *robot* communicates Δd.

3.3 Hierarchy of relaxation rates

Finally, the following hierarchy of relaxation rates ensures that the heading direction of the *follower* robot relaxes to the attractor solutions as they change due to varying sensory information and varying information communicated by the *leader*:

$$\lambda_{\mathrm{col}} \ll c_{\mathrm{col}}, \quad \lambda_{\mathrm{obs}} \ll c_{\mathrm{obs}}. \tag{17}$$

See (e.g. Bicho et al, 2000) for how to set the relaxation rates for the *leader*'s dynamic systems.

4. IMPLEMENTATION AND RESULTS

The complete dynamic architectures were implemented and evaluated on the robots. In the implementation the dynamics of heading direction and path velocity are integrated numerically using the forward Euler method. Sensory and communicated information is acquired once per computation cycle. The cycle (step) time is measured and is approximately 50 ms for each robot. As the time step must be smaller than the fastest relaxation time on the systems, this imposes minimal time scales on the entire dynamic architectures. Thus the computational cycle time is the limiting factor for determining the relaxation times of the dynamics in real time units and thus for the overall speed at which the robots' behavior evolves. Because the systems operate close to attractors of known stability, the time scales, or reversely the relaxation rates, can be set as a function of the computation cycle and thus guarantee the numerical stability. The rates of change of robots' heading direction obtained from their heading direction dynamics directly specify the angular velocity of the robots for rotation around their center. This can be translated into the difference between left and right wheel rotation speed. The path velocity specifies the average rotation speed of both wheels. Together, the rotation speeds of both wheels can be computed and sent as set points to the velocity servos of the two motors.

The most striking feature of the robots is their smooth behavior. This is due to how the dynamic approach permits information from various sources to affect in a graded fashion the generated behavior. We filmed the robotic system in a task scenario where they transport a long object in a cluttered indoor environment. Figures 5 and 6 illustrate the robots' behavior through a sequence of video images[7] . The situation is a scenario testing the ability to carry the object while simultaneously coping with situations where obstacle avoidance is in conflict with the robots' task. As exhibited the robots move smoothly and around the obstacles. Their ability to transport the object in narrow curves is also shown.

5. CONCLUSION AND FUTURE WORK

We have demonstrated how attractor dynamics can be used to design and implement a distributed dynamic control architecture that enables a team of two mobile robots, without force/torque sensors and equipped solely with low-level sensory information, to carry a long object and simultaneously avoid obstacles. The explicit required communication between robots is minimal. The *follower* robot only needs to receive from the *leader* its path velocity, v_{leader}. The robots have no prior knowledge of their environment. As the sensed world changes the systems change the planning solutions adequately. The robots' behavior is generated by time series of attractor solutions. The benefit is that the robotic system is robust against perturbations. Results show the movement of the robots while carrying a long object in cluttered indoor environments. The robots' behavior is stable and the generated trajectories are smooth. The demonstrated robotic system has an obvious application. Near future work is concerned with the design and implementation of distributed control architecture for larger teams of autonomous robots that cooperatively carry large size objects.

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[7] see videos in http://www.dei.uminho.pt/pessoas/estela/

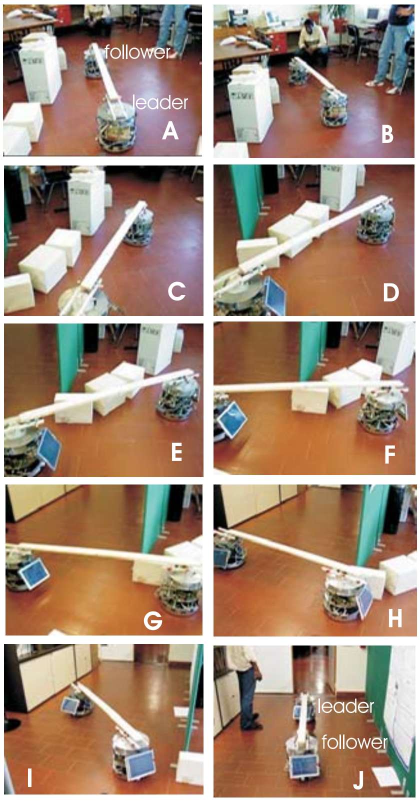

Fig. 5. Sequence of video images illustrates the motion of the robots while transporting the object. Initially, the robots are placed as indicated in Panel A. The *leader* moves toward the defined target location. The *follower* starts by steering behind the *leader* (Panels A - C). In panel D the *leader* starts turning right. From this point on the *follower* steers so that it follows the *leader* and simultaneously avoids collisions with the obstacles (Panels D - I). Once it is possible (Panel J) the *follower* drives again behind the *leader* until the final target position is reached.

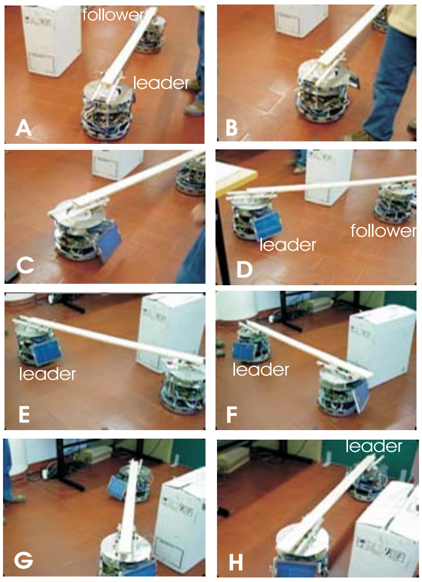

Fig. 6. The robots circumnavigating a box while carrying the long object. This challenges the robots' ability to make narrow curves in cluttered environments.

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REFERENCES

Ahmadabadi, M N and E Nakano (2001). A constraint and move approach to distributed object manipulation. *IEEE Transactions on Robotics and Automation* **17**(2), 157–172.

Althaus, P, H Christensen and F Hoffmann (2001). Using the dynamical systems appproach to navigate in realistic real-world environments. In: *Proc. 2001 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems.* ICAR 2003. pp. 1023–1029.

Arai, T and J Ota (1997). Dwarf intelligence - a large object carried by seven dwarves. *Robotics and Autonomous Systems* (21), 23–35.

Bicho, E and G Schöner (1997). The dynamic approach to autonomous robotics demonstrated on a low-level vehicle platform. *Robotics and Autonomous Systems* (21), 23–35.

Bicho, E, L Louro, N Hipolito, S Monteiro and W Erlhagen (2003). Motion control of a mobile robot transporting a large size object in cooperation with a human: a nonlinear dynamical systems approach. In: *Proc. IEEE 11th International Conference on Advanced Robotics.* ICAR 2003. pp. 197–203.

Bicho, E, P Mallet and G Schöner (2000). Target representation on an autonomous vehicle with low-level sensors. *The International Journal of Robotics Research* **19**(5), 424–447.

Large, E W, H I Christensen and R Bajcy (1999). Scaling the dynamic approach to path planning and control: Competition amoung behavioral constraints. *The International Journal of Robotics Research* **18**(1), 37–58.

Schöner, G, M Dose and C Engels (1995). Dynamics of behavior: Theory and applications for autonomous robot architectures. *Robotics and Autonomous Systems* **16**, 213–245.

Steinhage, A (1998). *Dynamical Systems for the Generation of Navigation Behavior.* Shaker Verlag. Aachen.

Takeda, H, Z Wang and K Kosuge (2003). Collision avoidance system for two tracked mobile robots transporting a single object in coordination based on function allocation concept - utilization of environmental information by visual sensor. In: *Proc. IEEE 11th International Conference on Advanced Robotics.* ICAR 2003. pp. 488–493.