

Dynamic Control of a Mobile Manipulator

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Abstract

This paper deals with the dynamic control of a mobile manipulator operating in busy environments such as hospitals. Major requirements within this application domain are safe, robust, and reliable task execution so that people can gain confidence in the robotic assistant. As a consequence the robot should move with smooth motions about both known and unknown obstacles. In our approach, this is achieved using collision-free dynamic bands, which represent a set of feasible paths for the robot platform and the manipulator. These bands have to interact in a way which satisfies both kinematic and dynamic constraints. Finally, paths within these bands have to be selected and tracked at execution time.

1 Introduction

In recent years service robots have been introduced into a variety of non-industrial application areas such as entertainment, health and home-care services. These robotic assistants usually comprise an omnidirectional locomotion platform and an appropriate manipulator. Compared to industrial applications they operate in busy environments and interact with people. Hence, the desired service tasks must be executed in a smooth, safe, robust and reliable manner so that people in the vicinity of the robot feel comfortable with it.

The problem of robot motion planning and robot motion control has been investigated by many researchers. In the artificial potential field method [1, 2] an attractive force from the goal and repulsive forces due to obstacles guide the robot without collision to its destination. A diffusion based method is presented in [3], where the robot finds its way to the goal following a diffusion gradient. A similar approach based on fluid dynamics is described in [4]. Recent approaches, which combine the advantages of global and local aspects of

the motion planning problem, have been proposed in [5, 6, 7].

For mobile manipulation tasks both platform and manipulator need to be controlled. These two subsystems, when combined, usually form a redundant dynamic system. Much research has been done to solve the problem of controlling a redundant mobile manipulator. In [8] task specific weighting factors to individual degrees of mobility and manipulability were introduced to allow a trade-off between mobility of the platform and manipulability of the robot arm. A method of decoupled platform and manipulator motion is proposed in [9]. Manipulator motion is complemented by appropriate motion of the platform to maintain the desired end-effector motion. Another method based on the separation of the two motion subsystems is presented in [10], where a fuzzy penalty approach derives the platform motion required to maintain good manipulability and sufficient clearance from obstacles.

In our approach, we use dynamic bands as a representation of collision-free dynamically feasible paths for both, platform and manipulator.

The paper is organized as follows: in the next section, an exact problem formulation is given. Sec. 3 shows how goal directed motion planning including robot dynamics can be achieved. In Sec. 4 deals with the execution of the planned motion ensuring sufficient reactivity. Simulation results are presented in Sec. 5, while in Sec. 6 conclusions are drawn and future directions are presented.

2 Control Problem Formulation

We consider a mobile robotic assistant for service applications, comprising a mobile platform and a robotic arm. The platform dynamics are given by

$$\begin{aligned} \dot{x} &= v \cos \varphi & |v| &\leq v_{max} \\ \dot{y} &= v \sin \varphi & |u_s| &\leq u_{s,max} \\ \dot{\varphi} &= u_s & |u_d| &\leq u_{d,max} \\ \dot{v} &= u_d \end{aligned} \quad (1)$$

where x and y denote the robot position with respect to an inertial coordinate system, φ is the steering angle, and v corresponds to the robot velocity. The robot is equipped with an M degree-of-freedom manipulator with all revolute joints, where α_i denotes the angular position of joint i . The arm dynamics is assumed to be given by

$$\begin{aligned} \dot{\alpha}_i &= \omega_i & |\alpha_i| &\leq \alpha_{i,max} \\ \dot{\omega}_i &= \nu_i & |\omega_i| &\leq \omega_{i,max} \\ & & |\nu_i| &\leq \nu_{i,max} \end{aligned} \quad i = 1 \dots M. \quad (2)$$

In contrast to industrial robots, a personal assistant robot does not work in a dedicated environment and so shares its workspace with people. Hence, mobile manipulation quality cannot easily be assessed by the objective evaluation of classical metrics, such as execution time or overall path length. Rather, the goal is to achieve a smooth, predictable motion that appears goal-oriented, so that people quickly gain confidence and feel comfortable when living with the robot.

The easiest way to achieve these subjective goals would be to precisely pre-plan mobile manipulation tasks. However, there is usually much uncertainty in the knowledge of the environment. As a result, most plans would be discarded because of unanticipated changes in the environment. On the other hand, purely reactive maneuvering makes it difficult to consider robot dynamics. Furthermore, it is desirable that evasive maneuvers for avoiding suddenly appearing unknown obstacles are smoothly integrated into the current execution flow.

Hence, we propose to keep a band of free space as a rough guideline to the goal for both platform and manipulator. The band considers dynamical constraints of the robot and is constructed on the basis of the current uncertain knowledge about the environment. As a result, new sensor information is included in two ways. The robot immediately reacts to suddenly appearing obstacles by performing evasive maneuvers within the band of free space. In addition, the band is locally adapted to the new obstacle configuration without the need of complete replanning.

For the later discussion, terms describing the decomposition of typical robot tasks are introduced: during the *long distance locomotion* phase, the robot is traveling between workplaces. In this phase, sufficient fast motion and safe obstacle avoidance are issues, while the manipulator is in a transport position. During the *mobile manipulation* phase, manipulator and platform motion have to be coordinated.

Typical mobile manipulation tasks can be classified with respect to the type of end-effector motion as: 1. Tasks with given end-effector path, for example, opening doors. 2. Tasks with a fixed goal-point of the

end-effector, for example, fetching objects. 3. Tasks with a variable end-effector goal-point, for example, when teaching the robot by manually moving its end-effector.

3 Goal directed motion planning including robot dynamics

In a first step, collision-free local regions for platform and manipulator are introduced, called bubbles [5]. Bands, which represent sets of feasible paths to a goal configuration, are created by the concatenation of bubbles. To account for the robot dynamics as well as surrounding obstacles, artificial forces result in a dynamic deformation of the bands.

3.1 Definition of a collision-free local region

Bubbles are either constructed in the configuration space or in the workspace of the robot as a representation of collision free regions. Hence, the robot geometry is considered by enlarging the obstacles or by enlarging the bubbles, respectively.

We propose two approaches for considering not only obstacles, but also dynamic constraints of the robot. The *implicit* approach considers constraints by an appropriate concatenation of individual bubbles. In the *explicit* approach, bubbles are constructed in the full state space and are defined as the set of all feasible states, that can be reached via paths with a given maximum length. In the latter case, bubble generation is numerically intensive and can for example be performed using dynamic programming. It is hardly suitable for real-time implementation of the motion planner.

To combine the simplicity of the implicit approach with the representational power of the explicit approach, the bubble is constructed in the x/y -subspace, where the remaining states determine bubble attributes like orientation and size.

Bubbles for platform motion The bubbles for platform motion are constructed in such a way, that it is always possible for the robot to come to a complete stop within the bubble.

We propose the following definition: A bubble contains all paths in the x/y -plane which are obtained starting from an initial system state $(x_0, y_0, \varphi_0, \pm v_0)$ leading to any state $(x_e, y_e, \varphi_e, v_e)$ with $v_e = 0$ when maximum deceleration and arbitrary steering velocities within $[-u_{s,max}, u_{s,max}]$ are applied. If the necessary distance to come to a complete stop is denoted s , the bubble borders are the end points of shortest

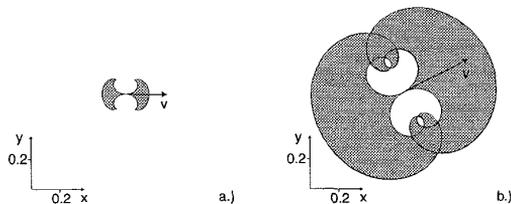


Figure 1: Bubbles in configuration space: a) $v = 0.4 \text{ m/s}$, $\varphi = 0$, b) $v = 0.8 \text{ m/s}$, $\varphi = 0.5$.

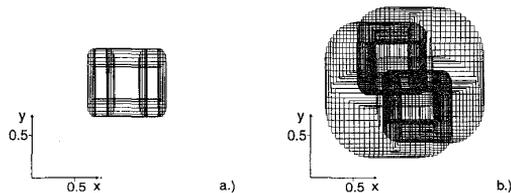


Figure 2: Bubbles in workspace for a quadratic platform: a) $v = 0.4 \text{ m/s}$, $\varphi = 0$, b) $v = 0.8 \text{ m/s}$, $\varphi = 0.5$.

paths with length s and can be calculated by means of Pontrjagin's maximum principle. In order to obtain a symmetric bubble, positive and negative initial velocities are considered.

The state vector associated with the bubble defines its center-point (x_0, y_0) , its size according to the velocity v_0 and its orientation according to the steering angle φ_0 . Fig. 1 and Fig. 2 depict bubbles for different velocities and steering angles in the configuration space and in the workspace, respectively.

Bubbles for manipulator motion Collision-free regions for manipulator are constructed in the configuration space, i.e., the space defined by the generalized joint coordinates. These bubbles are represented by ellipsoids.

In order to consider the system dynamics the complete state vector is associated to the bubble. Analogous to the platform bubbles, the joint angle velocities are assigned to the length of the corresponding main axis of the ellipsoid. Hence, the allowed motion velocity depends on the distance to surrounding obstacles.

3.2 Constructing Global Collision-Free Bands to the Goal

Since bubbles represent local collision free regions, motion planning is equivalent to finding a sequence of overlapping bubbles leading from a start to a goal configuration. Such a band is constructed for both the

platform and the manipulator.

The advantages of using a single band for each of the dynamic subsystems are numerical efficiency and ease of transition from a locomotion task to a mobile manipulation task. Furthermore, obstacles which are relevant either for the manipulator or for the platform can be considered more effectively.

Initial bands are constructed as follows:

Long-Distance Locomotion The initial band for the platform can be obtained based on standard path planning methods, for example a road map or cell decomposition. Since such an initial path is collision free by definition, a sequence of overlapping bubbles can be constructed on this path representing a band to the goal. While the arrangement of bubbles may not be optimal at this time, it will be modified to account for the robot dynamics.

Mobile Manipulation For mobile manipulation tasks with a fixed end-effector path the allowed configurations for the platform are not only restricted by surrounding obstacles but also by the manipulator kinematics. Considering the set of points on the end-effector path, it is clear that only a certain set of platform configuration exists which allows related end-effector positions. Hence, an initial band must be constructed in this constrained space of the x/y -plane.

For each bubble of the platform band, a corresponding bubble of the arm band is constructed in such a way that the resulting end-effector position corresponds to any point of the desired path. The end points of the end-effector path are represented by the first and last pair of bubbles, respectively.

3.3 Band Modification and Interaction Between Bands

The modification of bands, and the interaction between them, is an iterative process which modifies the form of the bands in order to fulfill obstacle and system dynamics constraints. At any time all available information about the environment is incorporated. During motion execution, for example, additional obstacles might be detected by the on-board sensor system within its field of view.

For band modification artificial forces are applied which result in bubble movement. Besides the position of the bubbles, the remaining state variables associated with the bubbles are also modified. The velocity attributes of two adjacent bubbles, for example, cannot be selected arbitrarily because of the bounded acceleration of the system. On the other hand, the ma-

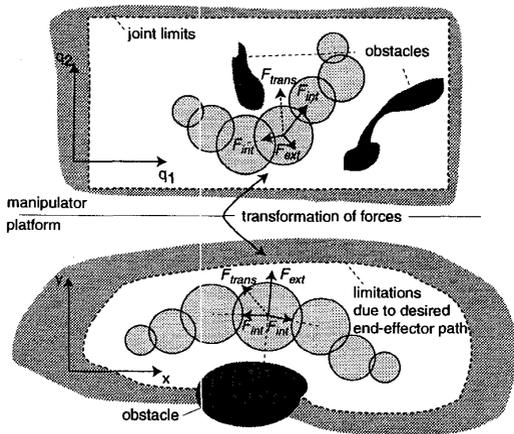


Figure 3: Bubble bands for platform and manipulator

ximum size of a bubble is restricted by the surrounding obstacles.

The following items illustrate the band modification process:

- **Bubble overlap:** Internal forces between two adjacent bubbles ensure sufficient overlap.
- **Obstacle avoidance:** External forces push the bubbles away from obstacles.
- **Band convergence:** Damping forces are applied to ensure that the band converges to an equilibrium for a static environment.
- **Bubble size:** Bounded velocity and acceleration of the system as well as surrounding obstacles determine the size of a bubble.
- **Bubble orientation (platform):** Internal momentums, which try to align the bubbles and external momentums due to obstacles, affect the orientation.
- **Manipulability (arm):** Additional forces are applied to achieve configurations, where good manipulability is ensured.

Interaction between the individual bands of platform and arm is achieved by transforming the arising forces back and forth, Fig. 3. For example, forces acting on the arm bubbles not only push the end-effector to a new position, but also act on the platform via the arm base point. However, for a given end-effector path, forces are constrained in such a way, that lateral deviations from the path are avoided.

4 Motion execution including reactive maneuvers

For motion execution it is necessary to track paths within the bands. One approach to obtain a path is to use a reference model in order to connect adjacent bubbles. The resulting motion of the model implicitly generates a trajectory. Such a reference model can be designed by fuzzy-techniques, as in [11]. A second approach is to explicitly calculate a path between two adjacent bubbles which yields to a reference trajectory by time parametrization.

Control of platform For platform motion control, the corresponding reference trajectory $(x_r(t), y_r(t))$ is tracked by a nonlinear controller designed via integrator backstepping. The corresponding control law is derived by introducing the state error variables $x_e = x - x_r$ and $y_e = y - y_r$ for the first two system states. The resulting equations are

$$\begin{aligned}\dot{x}_e &= v \cos\varphi - \dot{x}_r \\ \dot{y}_e &= v \sin\varphi - \dot{y}_r \\ \dot{\varphi}_e &= u_s \\ \dot{v}_e &= u_d.\end{aligned}\quad (3)$$

We now consider v and φ as inputs of the two-dimensional subsystem represented by the first two state equations. A possible Liapunov function for this subsystem and its derivative are

$$V_1 = \frac{1}{2} (x_e^2 + y_e^2) \quad \dot{V}_1 = x_e \dot{x}_e + y_e \dot{y}_e \quad (4)$$

Now we substitute \dot{x}_e and \dot{y}_e according to (3) and choose as inputs to the subsystem

$$\begin{aligned}\varphi &= \text{atan} \frac{\alpha_y}{\alpha_x} \\ v &= \alpha_x \cos\varphi + \alpha_y \sin\varphi\end{aligned}\quad (5)$$

with

$$\begin{aligned}\alpha_x &= a(x_r - x) + \dot{x}_r, \quad a > 0 \\ \alpha_y &= b(y_r - y) + \dot{y}_r, \quad b > 0.\end{aligned}\quad (6)$$

Finally, the following expression for the derivative of the Liapunov function is obtained, which is a negative semi-definite function:

$$\dot{V}_1 = -a(x - x_r)^2 - b(y - y_r)^2. \quad (7)$$

We now introduce new state variables

$$\begin{aligned}z_1 &= x_e \\ z_2 &= y_e \\ z_3 &= \varphi - \text{atan} \frac{\alpha_y}{\alpha_x} \\ z_4 &= v - \alpha_x \cos\varphi - \alpha_y \sin\varphi.\end{aligned}\quad (8)$$

The Liapunov function for the new state variables and its derivative are

$$V_2 = \frac{1}{2}(z_1^2 + z_2^2 + z_3^2 + z_4^2) \quad (9)$$

$$\dot{V}_2 = \dot{V}_1 + z_3 \dot{z}_3 + z_4 \dot{z}_4. \quad (10)$$

For the derivatives of the state variables z_3 and z_4 we obtain

$$\begin{aligned} \dot{z}_3 = \dot{\varphi} - \frac{\alpha_x(b(\dot{y}_r - v\sin\varphi) + \ddot{y}_r)}{\alpha_x^2 + \alpha_y^2} \\ + \frac{\alpha_y(a(\dot{x}_r - v\cos\varphi) + \ddot{x}_r)}{\alpha_x^2 + \alpha_y^2} \end{aligned} \quad (11)$$

and

$$\begin{aligned} \dot{z}_4 = -\alpha_x \sin\varphi \dot{\varphi} + \alpha_y \cos\varphi \dot{\varphi} + a v \cos^2\varphi + b v \sin^2\varphi \\ - (a\dot{x}_r + \ddot{x}_r)\cos\varphi - (b\dot{y}_r + \ddot{y}_r)\sin\varphi + \dot{v}. \end{aligned} \quad (12)$$

By selecting $\dot{z}_3 = -z_3$ and $\dot{z}_4 = -z_4$, we obtain the following nonlinear expression for the tracking controller of the platform

$$\begin{aligned} u_s = \frac{\alpha_x(b(\dot{y}_r - v\sin\varphi) + \ddot{y}_r)}{\alpha_x^2 + \alpha_y^2} \\ - \frac{\alpha_y(a(\dot{x}_r - v\cos\varphi) + \ddot{x}_r)}{\alpha_x^2 + \alpha_y^2} - \varphi + \text{atan} \frac{\alpha_y}{\alpha_x} \end{aligned} \quad (13)$$

$$\begin{aligned} u_d = \alpha_x(\sin\varphi \dot{\varphi} + \cos\varphi) - \alpha_y(\cos\varphi \dot{\varphi} + \sin\varphi) \\ + (a\dot{x}_r + \ddot{x}_r)\cos\varphi - (b\dot{y}_r + \ddot{y}_r)\sin\varphi \\ - v(1 + a\cos^2\varphi + b\sin^2\varphi). \end{aligned} \quad (14)$$

Platform reactivity During motion execution, sufficient reactivity has to be guaranteed. This is especially important for platform motion during fast locomotion tasks when suddenly appearing close obstacles may not allow band deformation in time. Hence, a track bubble is used which represents the actual state of the system. If the track bubble for platform motion intersects with a suddenly appearing obstacle, the robot will slow down with maximum deceleration. During this evasive maneuver, the steering velocity can be chosen arbitrarily because no further obstacles can be reached thanks to the definition of the bubble.

Control of manipulator For motion control of the manipulator the joint angles defined by the center points of the bubbles can be used for anticipatory control. However, connecting two adjacent bubbles for manipulator and platform might result in a deviation of the end-effector from its path. Hence, an additional feedback controller based on Jacobian techniques is proposed to keep tracking errors low.

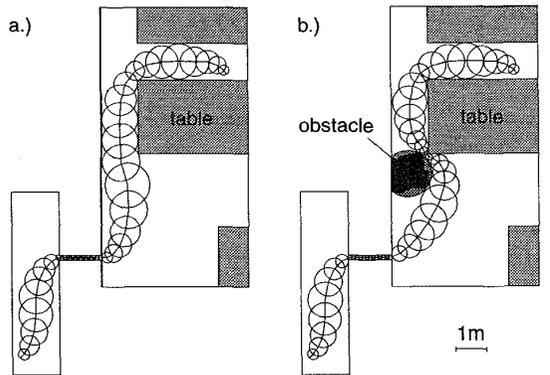


Figure 4: Bubble bands for long distance locomotion a) without and b) with additional obstacle.

5 Simulation Results

The mobile manipulator considered comprises a quadratic locomotion platform and a 2-DOF scara-type manipulator mounted at one corner the platform. In our implementation we use bubbles in the configuration space of both, platform and manipulator, where the platform bubbles are approximated by circles.

In the first scenario, we consider a long distance locomotion path between two rooms with a narrow door passage. Fig. 4a shows the bands after 20 iterations. In Fig. 4b an additional obstacle results in band deformation. The size of the bubbles corresponds to the related velocity during task execution, so that narrow passages are traveled with low speed.

In the second scenario a mobile manipulation task with given end-effector path going over a table is considered. The optimal arm configuration is defined by an optimal angle of the first joint and an optimal distance between end-effector and base. Fig. 5 shows the initial and the final band related to the platform motion. The corresponding robot configuration (platform and arm) in the workspace are depicted in Fig. 6. The resulting motion is characterized by a compromise between good manipulability and sufficient clearance from the table.

6 Conclusions and Future Directions

We have suggested a motion control method for a manipulator mounted on a mobile platform. This method is aimed at service applications and thus considers the specific requirements that arise when robot and humans share the same workspace. Furthermore,

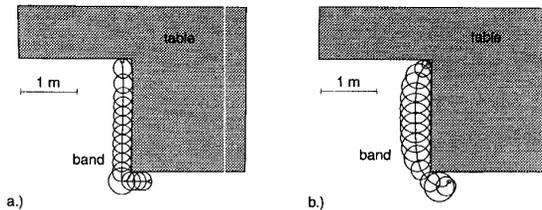


Figure 5: Bubble bands for the platform, a) initial and b) after 30 iterations.

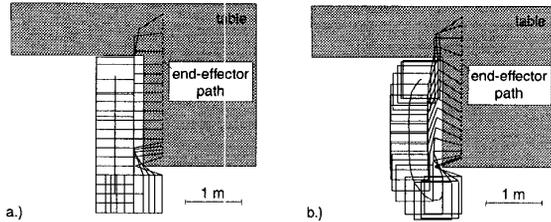


Figure 6: Resulting robot configuration, a) initial and b) after 30 iterations.

our technique considers dynamic restrictions of both platform and manipulator.

For a number of sub-problems, several alternative solutions have been provided without giving definitive advice about which one to select in a given application. This includes different types of motion between bubbles and the representation of obstacles in the configuration space or workspace, both of which will be further investigated.

We are currently exploring generalizations of our approach, in particular, using reinforcement learning to incorporate user preferences and employing case-based reasoning techniques for quickly re-using of already stored motion plans which are appropriate for the current situation.

Current investigations also include a number of interesting and important issues excluded here for the sake of brevity. Among these are the automatic generation of appropriate end-effector paths and the use of learning agents for guiding the robot from bubble to bubble.

References

[1] J. Guldner, "Lokale Kollisionsvermeidung für mobile Roboter mittels künstlicher harmonischer Dipol-Potentiale," *Automatisierungstechnik*, Vol. 45, pp. 24-35, 1997.

[2] E. Rimon, D.E. Koditschek, "Exact Robot Navigation Using Artificial Potential Functions," *IEEE Trans. on Robotics and Automation*, Vol. 8, pp. 501-518, 1992.

[3] G. Schmidt, K. Azarm, "Mobile Robot Navigation in a Dynamic World Using an Unsteady Diffusion Equation Strategie," *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Vol. 1, pp. 642-647, 1992.

[4] D. Keymeulen, J. Decuyper, "The Fluid Dynamics Applied to Mobile Robot Motion: The Stream Field Method," *Proc. of the 1994 IEEE Int. Conf. on Robotics and Automation*, Vol. 1, pp. 378-385, 1994.

[5] S. Quinlan, O. Khatib, "Elastic Bands: Connecting Path Planning and Control," *Proc. of the 1993 IEEE Int. Conf. on Robotics and Automation*, Vol. 2, pp. 802-807, 1993.

[6] M. Khatib, H. Jaouni, R. Chatila, J.-P. Laumond, "How to Implement Dynamic Paths," *Experimental Robotics, The Fifth Int. Symp., Barcelona, Catalonia, Lecture Notes in Control and Information Sciences*, Eds.: A. Casals, A. Almeida, pp. 289-300, 1997.

[7] M. Khatib, H. Jaouni, R. Chatila, J.-P. Laumond, "Dynamic Path Modification for Car-Like Nonholonomic Mobile Robots," *Proc. of the IEEE Int. Conf. on Robotics and Automation*, Vol. 4, pp. 2920-2925, 1997.

[8] H. Seraji, "An on-line Approach to Coordinated Mobility and Manipulation," *Proc. of the 1993 IEEE Int. Conf. on Robotics and Automation*, Vol. 1, pp. 28-33, 1993.

[9] U.M. Nassal, "An Approach to Motion Planning for Mobile Manipulation," *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Vol. 2, pp. 831-838, 1994.

[10] M. Seidl, C. Fischer, "Feed-Forward Locomotion Control Strategy for a Manipulator Mounted on a Mobile Platform," *TELEMAN-HCM European Union Undergraduate Students Telerobotics Congress*, pp. 101-106, 1995.

[11] S. Maier, U. Hanebeck, "Fuzzy-Guidance of Omnidirectional Mobile Robots Including Sensor-Based Obstacle Avoidance," *TELEMAN-HCM European Union Undergraduate Students Telerobotics Congress*, pp. 95-100, 1995.

[12] Z. Jiang, H. Nijmeijer, "Tracking Control of Mobile Robots: A Case Study in Backstepping," *Automatica*, Vol. 33, No. 7, pp. 1393-1399, 1997.

[13] B. Thuilot, B. d' Andrea-Novel, A. Micaelli, "Modeling and Feedback Control of Mobile Robots Equipped with Several Steering Wheels," *IEEE Trans. on Robotics and Automation*, Vol. 12, pp. 375-390, 1996.