Mobile Manipulation — A Mobile Platform Supporting a Manipulator System for an Autonomous Robot

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In most autonomous mobile manipulator systems, the mobile platform is only used for transporting the manipulators between spatially distributed assembly stations. In general, the mobility of the platform can be exploited to enlarge the workspace of a manipulator system (with one or multiple arms) at a single assembly station. In this article various approaches to the cooperation of a mobile platform with on-board manipulators are investigated. A concept for one type of cooperation is introduced and applied to an existing mobile two-arm system.

1 INTRODUCTION

A mobile manipulator is a mobile platform that carries one or more manipulators. Usually, such a system has redundant kinematics with respect to the tool-center-point (TCP) of the manipulators, which is usually not exploited. Though the general problem of manipulators with redundant kinematics has been extensively studied, up to now little attention has been paid to the potential of increasing the workspace by taking advantage of the mobility of the platform. The majority of present work on mobile robots is concerned with navigation and collision avoidance behaviours. On-board manipulators are considered separately.

In this article different approaches for the integration of mobility and manipulation are discussed and a new concept for the realisation of this integration on a mobile two-arm system is presented. The testbed to which the developed concepts are applied is KAMRO, the Karlsruhe Autonomous Mobile Robot. The mobile platform of this robot system has three degrees of freedom (DoF), two translational ones and one rotational, that result from the omnidirectional drive system. The platform is equipped with ultrasonic sensors for collision avoidance. The manipulator system consists of two PUMA-type manipulators with six DoF, which are mounted on the platform in a hanging configuration. Each manipulator is equipped with a force-/torque sensor with an integrated electric gripper for tactile operations and a hand-eye camera for the enhancement of the object recognition.

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So far the mobile platform has been used for supporting the manipulators as follows: the mobile platform navigates between different assembly stations, takes a reference position and keeps this position until the manipulators have finished their tasks; afterwards, the platform moves to the next assembly station. Thus, the platform is not in motion while the manipulators are active. In all cases, in which the objects to be manipulated are situated in a small and constant region, all tasks can be executed that way. There exist other situations, in which the platform has to be moved along the assembly station to enable the manipulators to perform their tasks. Then, a cooperation of the platform with the manipulator system may be necessary.

For the cooperation of a manipulator system and a mobile platform, planning problems have to be solved, as well as problems of control. Combining a manipulator with a mobile platform results in a system with redundant kinematics. Researchers investigating control systems with redundant kinematics mainly consider manipulators with more than six degrees of freedom (DoF)[1], [2]. On the other hand, path planning approaches for mobile manipulators have been developed, in which the manipulators are considered fixed during the motion [3].

In the following, articles considering manipulators and a mobile platform as an integrated system are listed: in [4] a method is introduced that allows a mobile manipulator system to exert a definite force on a moving object, e.g., to transport it in cooperation with other robots. The mobile platform ensures that the manipulator is in a region of preferred configuration, to give it the possibility to react quickly to small disturbances without reaching the limits of the joint angles. The results presented in that paper were obtained with one manipulator with six DoF and a mobile platform with three DoF and non-holonomic constraints. In [5] the focus is on the control of the center of gravity to avoid the tumbling of the mobile manipulator. An operator guides the manipulator through a force input and the vehicle is controlled to maintain the center of gravity in an area where the stability of the mobile robot is guaranteed. A pseudo-inverse is used to compute the actuator velocities needed to achieve a definite velocity of the manipulator tip and to comply with the requirements associated with the center of gravity.

The system introduced in [6][7] realizes methods for executing wide-range motions with a reactive control system, which moves the platform and manipulator to avoid collisions. The goal is to get the manipulator in such a configuration that a subsequent assembly task can be performed without delay. The inertial properties of holonomic mobile manipulation systems and strategies for their coordination and control are the focus of [8]. Based on the operational space formulation a model for the robot dynamics is being developed. The mobile base is viewed as a "macro-mechanism" whereas the arm is a fast and accurate "mini"-device. The key idea is the notion of *kinematic consistency* that allows the generation of control torques, that do not change the dynamic properties of the mini device.

Accurate position control of a manipulator subject to inaccuracies introduced by the suspension of the mobile platform is dealt with in [9]. The dynamic properties of the manipulator as well as the dynamic properties of the mobile platform are taken into account. The experimental results that could be obtained with this control scheme are presented in [10]. A similar problem is investigated in [11]. There, the dynamic equations for a two-arm system on a freely moving space-platform are described. The two latter named articles do not regard the mobile platform as a component useful for *supporting* the manipulators, but as a source of disturbances in terms of optimal control.

In [12] a method for path planning for a mobile manipulator was developed, in consideration of the solutions of the inverse kinematic problem for general redundant mechanical systems. A sequence of tasks, consisting of position, orientation, force and torque values, is transformed into a sequence of configurations of the manipulator and the mobile platform. By means of a cost functional one of the variety of solutions resulting from the redundancy is chosen. A similar problem is dealt with in [13]. For two successive manipulation tasks, a configuration of the mobile base and manipulator has to be determined that complies with the requirements of both tasks and allows an optimal transition. The question of connecting these configurations by a trajectory has not yet been considered.

The design of a control system for a mobile manipulator is the main subject of [14], where all actuators are controlled in one loop. For a given trajectory, a performance functional, including several optimality criteria, is minimized off-line. The resulting trajectory in augmented coordinates is used to generate motion commands for the mobile platform and the manipulator system. This approach was implemented for a real system with nine DoF and has been extended in [15] to allow for sensory-based trajectory tracking. In [16] a control method is introduced, that is executable in real-time because of its efficiency. The redundant DoF introduced by the mobile platform are treated as additional joints of the manipulator. They are exploited to satisfy further user -definable constraints besides the position and orientation of the TCP. The result is presented in a simulation for a manipulator with three DoF and a mobile platform with only one DoF.

Since most research on this topic originally comes from the studies of kinematic redundant manipulators, some key issues for mobile manipulation have not yet been considered. The presence of obstacles is mostly neglected. Some platforms carry more than one manipulator. Coordinated motion control for such systems has not been considered either.

2 TYPES OF MANIPULATOR-PLATFORM COOPERATION

Considering the above mentioned literature there are principally three possibilities for the cooperation of a mobile platform and on-board manipulators respectively. for the exploitation of the inherent degrees of freedom of such a system. They differ in the degree of cooperation, in the complexity of the related problems, and in the power of increased manipulation capabilities. The three approaches are easily understandable looking at Figure 1 and 3. Here and in the following, six DoF for the manipulator and three DoF for the platform are assumed.

2.1 LOOSE COOPERATION

For the loose cooperation of a mobile platform and a manipulator the two subsystems are considered separate. A platform motion planner is responsible for the three DoF of the mobile platform and a manipulator motion planner for the six DoF of the manipulator. The platform serves for transporting the manipulator and increases the robot's workspace that way. Platform and manipulator are always moved sequentially, since there is no instance that ensures a simultaneous motion to be collision free.

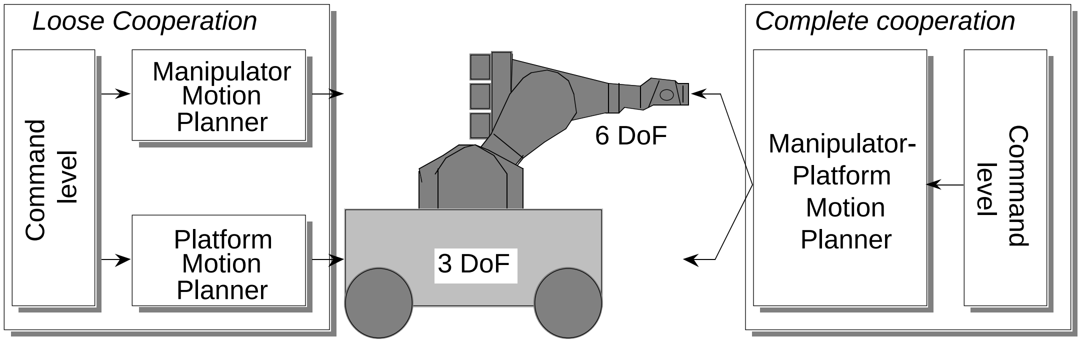

Figure 1: Structure of the loose cooperation and the complete cooperation

This kind of cooperation is suitable for moving the manipulator to spatially distributed assembly stations or to move it at an assembly station into a position that allows more efficient manipulation of an object. Kinematic redundancy has to be regarded only when a platform position has to be computed. The task of motion planning, an essential problem for autonomous systems, can be easily decomposed into two separate tasks. There are several methods for global and local path planning of mobile platforms that can be readily used for a loosely coupled system. Furthermore, there is no limitation for the number of manipulators mounted on the platform that can be supported that way. The mobile robot KAMRO has been performing assembly tasks using this kind of cooperation up to now.

2.2 COMPLETE COOPERATION

For the complete cooperation of a mobile platform and a manipulator, the two subsystems are regarded as one system with nine DoF. The mobile platform increases the DoF of the manipulator and the cooperating system has three redundant DoF. Platform and manipulator always move together for positioning the TCP. Nearly all the literature mentioned in section 1 is concerned with this kind of cooperation. One main difference to the scheme in section 2.1 is the presence of kinematic redundancy during the whole motion and not only for discrete times.

There are two different approaches to the resolving of kinematic redundancy for completely cooperating systems [17]: the first one is path inversion, where the complete end-effector trajectory is a priori known and transformed into joint motions by an off-line optimization procedure. Since this scheme is not appropriate for sensor-controlled manipulation tasks, another method used is local inversion. This scheme exploits only local properties of the end-effector motion, such as the end-effector velocity, and derives joints velocities using a local optimization procedure. In Figure 2, the two different schemes are shown for a one dimensional trajectory in task coordinates that has to be transformed into three joint trajectories.

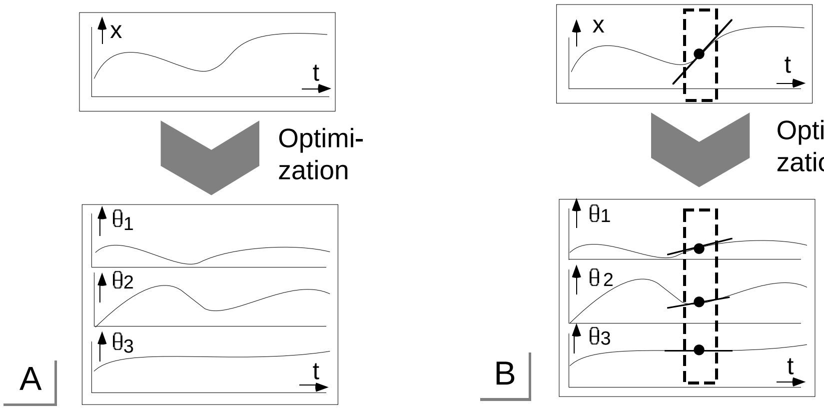

Figure 2: Path inversion (A) vs. local inversion scheme (B)

The complete cooperation is most appropriate as far as optimized dynamic motions are concerned, because the motion of the two subsystems is computed by an optimization procedure for all DoF involved. The complete cooperation offers at least theoretically optimal *mobility*, even under strong geometrical constraints.

On the other hand, *motion planning* under geometrical constraints is an essential feature for autonomous systems. It is a very demanding problem and at the moment not yet performable in real-time for such a completely cooperating system. Since all nine DoF have to be considered for the planning scheme, the complexity is even higher than that of the problem of fine motion planning for 6 DoF manipulators. The advantage of existing motion planning schemes for mobile platforms can not be exploited at all. If there are various manipulators on-board, which may be arranged in closed kinematic chains, there has to be a different control scheme for every arrangement of the manipulators to exploit the advantages of this type of cooperation.

2.3 TRANSPARENT COOPERATION

The transparent cooperation, which is described in the following, is designed to combine the advantages of the loose and complete cooperation and to avoid the named disadvantages for autonomous systems. The main idea is, that in a first step the end effector motion is made independent from the vehicle motion, i.e. if the vehicle is moving, the end effector position is not affected. Thus, the vehicle motion is transparent to the end effector. More formal, the platform motion does not result in an *external motion* of the manipulator but merely in an *internal motion*, i.e., the configuration of the manipulator is modified. To achieve this, a kinematic decoupling scheme has to be established, that is working in the manipulator control loop to compensate for the platform motion. The second step is to control the platform in such a way, that the manipulators are enabled to perform their tasks and their configuration is optimized with respect to some task specific cost function.

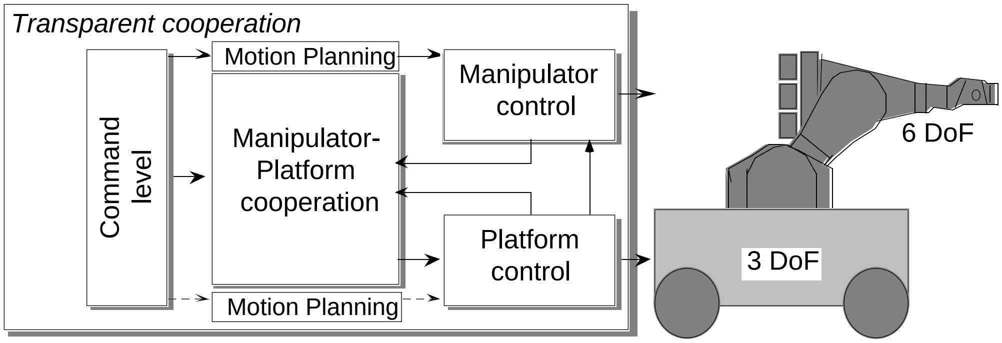

Figure 3: Structure of the *transparent cooperation*

This type of cooperation supports the usual way of transporting the manipulators by moving the platform as well as a coordinated motion with the platform continuously supporting the manipulators.

Motion planning for the manipulators can be performed using known schemes. If the platform has to be moved to enlarge the workspace of the manipulator, this can be done in parallel to the manipulator motion and in consideration of obstacles for the platform. Several manipulators can be mounted on the platform correspondingly to the loose cooperation.

3 A CONCEPT FOR THE TRANSPARENT COOPERATION

The concept for the transparent cooperation is designed for supporting a manipulator system with one or multiple arms as well as for supporting fixed sensors (e.g. camera systems). For the moment, only small-range motions are considered, i.e. motions at a single assembly station. A summary of possible tasks for a mobile two-arm system, e.g. the KAMRO described in the beginning, serves for the definition of the requirements.

3.1 ANALYSIS AND REQUIREMENTS

1) <u>Decoupled motion of the platform:</u>

During a motion of the mobile platform to support fixed sensors, e.g. to enlarge the visible area for a survey-camera, the TCP's of the manipulators should keep their current position in world coordinates respectively. complete the current manipulation task.

2) <u>Enlarging the work space of one manipulator:</u>

Three cases have to be considered:

A *Position-controlled manipulation task without explicit trajectory.*

The actual trajectory of the manipulator is of no importance. This occurs with tasks of transporting objects from one point to another. For long distance motions the manipulator may be partly passive until the platform reaches a region around the goal point. Supporting active manipulators permanently is still necessary since it may be useful when grasping heavy parts to minimize joint torques.

B *Position-controlled manipulation task with explicit trajectory:*

Here it is important to follow a given trajectory, because it has been planned to avoid obstacles or to perform some task along this trajectory (e.g. arc-welding). In this case, the motion of the mobile platform and the manipulator have to be coordinated permanently, since the manipulators are always active.

C *Sensor-controlled manipulation task*

For force-guided or camera-guided manipulation tasks it is not possible to prescribe a certain goal point, for which the platform and manipulator configuration can be optimized. Therefore, a permanent coordination like in case B has to be established.

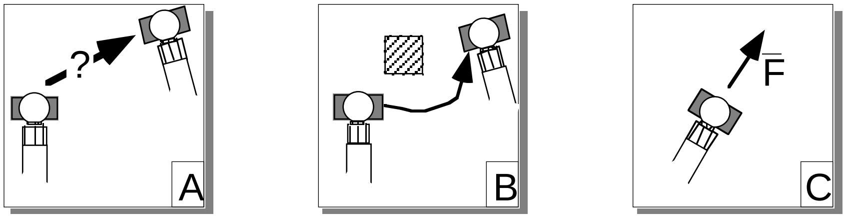

Figure 4: Types of manipulator operations

3) <u>Enlarging the workspace for multiple manipulators:</u>

For enlarging the workspace for two (or more) manipulators one of the cases in 2) is valid for each of the manipulators. Additionally there may be situations, where at least one manipulator performs a force controlled manipulation and at least one manipulator performs a position controlled manipulation and not all of them can be supported in parallel. The reason is, that there may occur kinematic conflicts that do not allow to perform all tasks simultaneously.

4) <u>Enlarging the work space for a kinematic chain:</u>

If two (or more) manipulators form a closed kinematic chain, then this case is in principle identical with 2). The difference is just the smaller and different shaped workspace of the chain; that is why supporting motions of the mobile platform are especially appropriate in this case.

There are the following requirements resulting from this tasks:

- The manipulator motion has to be potentially decoupled from the platform motion; the platform motion has to be sensor guarded to avoid collision danger.
- In order to achieve the enlargement of the workspace for one manipulator, one solution has to be chosen by means of a criterion out of the manifold resulting from the redundant kinematics. This criterion has to be different for different applications.
- For enlarging the workspace for several manipulators, a common path has to be chosen out of the multitude of supporting paths of the platform for each of the manipulators. The remaining redundancy can be exploited to optimize a criterion or to comply with the sensor based constraints. What makes supporting several manipulators more demanding compared to the case of one manipulator is the fact, that there may be situations where there is no common path to support all the manipulators. Such situations have to be resolved by sequentializing the manipulator motions.
- The problems arising with a closed kinematic chain are essentially the same as the ones for the enlargement of the workspace of a single manipulator.

There are several assumptions in this approach concerning the dynamics and the geometry of the subsystems manipulator and mobile platform, and concerning the planning environment:

- The end-effector motion has a higher bandwidth than the manipulator motion. This is necessary to compensate for small errors when performing sensor-controlled manipulation tasks.
- The maximum velocity of the mobile platform is higher than the desired velocity of the end-effector motion, since otherwise it is not possible to perform a cooperating motion along a complex trajectory over a long distance.
- There are several assumptions in this approach concerning the planning environment for the manipulator-system. It is assumed that there is a goal-oriented hierarchical planning system that generates motion commands for the manipulator system. These commands will now be redirected to the mobile manipulation planner, that decides,

whether this new command is consistent with the ones that are just processed and initiates the appropriate planning scheme for the platform. There is no explicit request for supporting the manipulators. The mobile manipulation planner decides itself which resources should be used to perform a motion command.

- The manipulator motion planner has knowledge about the geometric obstacles, so it can be assumed that the generated paths (the *external motion*) are collision-free for the manipulators. Since this planner is not informed about the platform motion, collisions resulting from the platform motion (*internal motions)* have to be avoided by the mobile manipulation planner.

3.2 STRUCTURE OF THE MANIPULATOR-PLATFORM COOPERATION

For planning the motion of the mobile platform to support the manipulators and to enlarge their workspace, a reactive approach is suggested. The a priori information concerning the kinematics of the manipulators and the geometry of the environment must be modelled appropriately to use it in an on-line planning scheme. The geometric obstacles are modelled using an approximate cell decomposition. This representation is derived from an CAD model of the assembly station and the robot that has been made using the 3D-editor of ROBCAD™. Another constraint for the platform motion is the workspace of the manipulators. Since the platform motion is transparent to the end-effector motion, the end-effectors can be assumed to move independently from the vehicle. On the other hand, the vehicle is not allowed to move in such a way that the manipulator base, which is fixed to the vehicle, leaves the manipulators workspace. Therefore, the region outside the manipulators workspace can be considered as an obstacle to the vehicle. In Figure 4, the different transformations into configuration space are summarized.

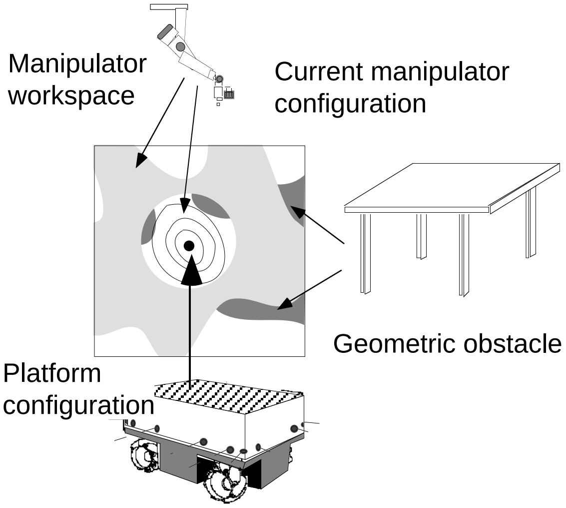

Figure 5: Transformation of different constraints into the vehicles configuration space

Furthermore, the dynamic information, e.g. the joint angles and velocities as well as unexpected obstacles for the platform have to be considered. Motion planning will be performed in a configuration space model, where dynamic information can be included by repetitive planning. As a result, we get a structure as depicted in figure 5.

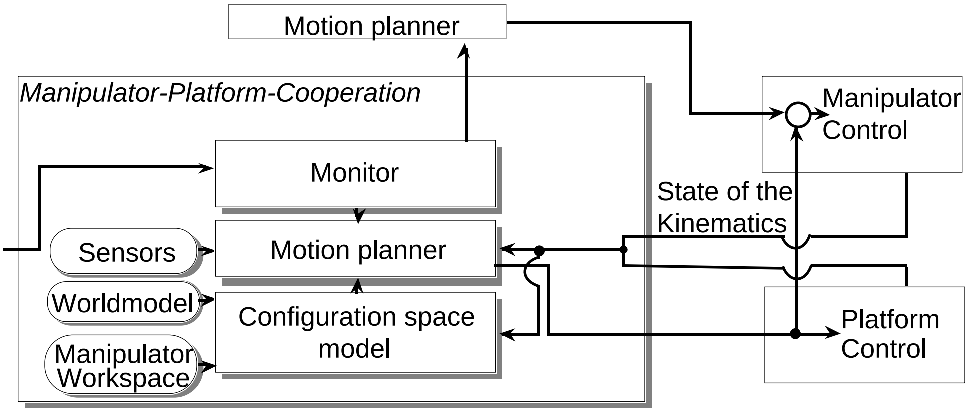

Figure 6: Structure of the planning system for the *transparent cooperation*

The information processing is done as follows: the monitor module receives motion commands from the task level planner. Motion commands for the vehicle are directly transmitted to the vehicle motion planner that performs a planning procedure that is beyond the scope of this paper. If there is a manipulation command, it has to be tested, whether the command can be processed immediately. There may be other manipulators working in such an area that the goal commanded for the last manipulator can not be reached without resulting in a kinematic conflict.

If the manipulator goal position is known and the kinematic test terminated successfully, a goal configuration for the platform can be computed. This is done using the model for the manipulators workspace and moving it to the end-effector's goal position. The remaining free space in the configuration space model is searched for an optimal configuration with respect to some task specific cost function. When this goal configuration has been found, the command can be transmitted to the manipulator motion planner.

In parallel, the planning cycle of the mobile manipulation motion planner starts to compute motion commands for the platform to obtain the desired support for the manipulators. Knowledge about the requirements during the motion (e.g. minimizing joint torques) or at the goal position (e.g. maximum manipulability[1]) can be used to select an appropriate cost function. This cost function is used for the local planning scheme that is working in the configuration space model. A gradient in a potential field established by the selected cost function is used as a local decision for the platform motion. If a goal configuration has been computed, a global path planning scheme can be set up to compute a global direction for the vehicle. A combination of this gradients is used to control the vehicle. This control output is also transmitted to the manipulator controller to allow for the kinematic decoupling. For multiple manipulators, this scheme can be easily extended by including their workspace into the configuration space model and establishing a cost function to value their configuration.

The following section deals with the problem of motion decomposition, which is a backbone for the transparent cooperation of manipulator and platform.

4 DECOMPOSING THE END EFFECTOR MOTION

One main topic of mobile manipulation is resolving the kinematic redundancy, what is explicitly done by the approaches using the complete cooperation. The scheme introduced here resolves redundancy in an implicit manner.

4.1 OUTLINE OF THE SCHEME

In contrast to many researchers who perform off-line decomposition of the TCP motion to obtain globally optimized trajectories[12][14], in this approach, a global optimization is merely established for the goal configuration [13], while the motion is decomposed on-line. The loss of optimality during motion is more than compensated by the gain in flexibility. This flexibility allows dynamic obstacles to be considered. Furthermore, multiple manipulators can be supported.

The end-effector velocity in world coordinates can be written as:

$$\dot{x}_{e/w} = T_1(x_{p/w})\,\dot{x}_{e/p} + T_2\,\dot{x}_{p/w}, \tag{1}$$

where $T_1(x_{p/w})$ is a transformation matrix to transform the end-effector motion from a platform-fixed coordinate system to world coordinates, which depends on the current configuration of the platform $x_{p/w}$. All the vectors have a dimension of 6, since they contain position and orientation. T_2 denotes the transformation matrix to transform the platform motion into end-effector motion. Rewriting this in matrix form and introducing the manipulator Jacobian J_m yields:

$$\dot{x}_{e/w} = \underbrace{\begin{bmatrix} T_1(x_{p/w})J_m & T_2 \end{bmatrix}}_{\mathbf{J}} \begin{bmatrix} \dot{\theta}_m \\ \dot{x}_{p/w} \end{bmatrix}. \tag{2}$$

A widespread approach for decomposing the end-effector motion is to use a pseudo-inverse of the Jacobian of the whole mobile manipulator:

$$\dot{\theta} = \begin{bmatrix} \dot{\theta}_m \\ \dot{\theta}_p \end{bmatrix} = J^+\dot{x} + (I - J^+J)\kappa, \tag{3}$$

where $J^+ = J^T\left(JJ^T\right)^{-1}$ is the Moore-Penrose generalized inverse of the Jacobian [1] and $\mathbf{J}$. is the mobile manipulator Jacobian from Eqn. (2). The last term is related to the *internal motion* of the system, which has no effect on the position or orientation of the end-effector. In that formulation, the additional degrees of freedom introduced by the mobile platform are treated as if they were additional joints. This approach is related to the research that is concerned with the control of redundant manipulators. The approach considered here is different in so far as the platform is used to control the internal motion alone and has no effect on the external motion:

$$\dot{\theta}_m = J_m^{-1}\,T_1^{-1}\left[\dot{x}_{e/w} - T_2\,\dot{x}_{p/w}\right], \tag{4}$$

$$\dot{x}_{p/w} = f(\theta_m, \dot{\theta}_m, \text{obstacles}). \tag{5}$$

Equation (4) outlines the principle of decoupled motion that is described in further detail in the following section. The control of the mobile platform is expressed by Equation (5), where we are free to realize a control function that complies with different requirements (controlling the manipulator configuration, avoiding obstacles etc.). Rewriting these equations in matrix form yields

$$\begin{bmatrix} \dot{\theta}_m \\ \dot{x}_{p/w} \end{bmatrix} = \begin{bmatrix} J_m^{-1}\,T_1^{-1} \\ 0 \end{bmatrix} \dot{x}_{e/w} + \begin{bmatrix} J_m^{-1}\,T_1^{-1}T_2\,\dot{x}_{p/w} \\ f(\theta_m, \dot{\theta}_m, \text{obstacles}) \end{bmatrix} \tag{6}$$

where the same decomposition into *external* and *internal motion* is evident.

The *external motion* of the end-effector is a result of the manipulator motion alone. The platform is used to control the internal motion of the manipulator and to perform local optimization for the configuration of the manipulator while avoiding obstacles for the mobile manipulator. Since the internal motion allows an optimal working point to be left without producing an error for the external motion, it is reasonable to assign this task to the mechanism with the slower dynamic response. The means to comply to this task is the establishment of a configuration space model of the environment and the consideration of the manipulator by introducing virtual obstacles and potential fields to value their configuration. This principle can easily be extended to the support of multiple manipulators.

4.2 THE PRINCIPLE OF DECOUPLED MOTION

There are two methods of interaction between the mobile platform and the manipulator system. First, the platform is requested to move in order to maintain the manipulators in an appropriate configuration (Eqn. 5). All the information concerning the manipulator tasks, their configuration and the environment is available for it. Since it is not known a priori how the platform will move to support the manipulators, the motion planner for the manipulators is not allowed to make any assumptions about this motion. It produces a desired trajectory in world coordinates and does not care whether it is executed by the manipulators only or in cooperation with the platform. For that reason, the motion of the mobile platform must be compensated for, and any supporting motion must be hidden from the manipulator motion planner (Eqn. 4). This principle is depicted in Figure 7. The figure on the left shows the case of a manipulator resting in a fixed world position while the platform is moving (in order to support another manipulator or in order to change the configuration of this one). The figure on the right shows another situation where the manipulator moves in world coordinates while the platform supports this motion. A prototype of this decoupling has been implemented on the mobile two-arm system KAMRO, the **K**arlsruhe **A**utonomous **M**obile **RO**bot [18].

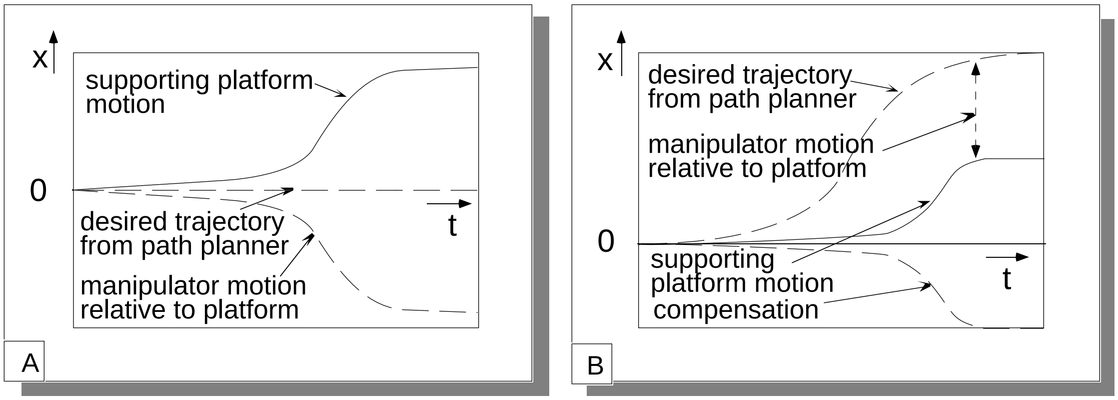

Figure 7: The principle of decoupled motion: a) manipulator resting in world position b) manipulator following a trajectory

For sensor-controlled manipulation tasks, the decoupling of the platform motion has another advantage, since the sensor control needs not to compensate for the platform motion. This compensation has already been made on the position control level. Hence, there are no (or only negligible) disturbances resulting from the platform motion.

5 CONTROLLING THE VEHICLES MOTION

While in the last section the compensation of the vehicles motion for the end-effectors position and orientation has been developed, this section is concerned with the control of the vehicles motion. The goal is to move the vehicle in order to support the manipulators. The requirements of the manipulators expressed in their joint space have to be transformed into the vehicles task space. Furthermore, a control function has to be set up, which allows to fulfill this requirements with fast dynamic response.

5.1 TRANSFORMING THE MANIPULATOR REQUIREMENTS

The current configuration of the manipulators is valuated by a simple cost-function, the weighed squared angular distance (WSAD), which has been modified to define a region in joints space, where no support from the vehicle is required:

$$c = \sum_{i=1}^{\mathrm{DoF}} \mathrm{k_i} \mathrm{f}(\theta_\mathrm{i}), \qquad f(\theta_i) = \begin{cases} 0 & \mathrm{f.}\, \underline{\theta} < \theta_i < \overline{\theta} \cdot \\ (\theta_i - \overline{\theta})^2 & \mathrm{f.}\, \theta_i > \overline{\theta} \\ (\underline{\theta} - \theta_i)^2 & \mathrm{f.}\, \theta_i < \underline{\theta} \end{cases} \tag{7}$$

The influence of the vehicle's motion is expressed by the following equation for the gradient:

$$\mathbf{g} = \left. \frac{\partial c}{\partial\, {}^{\mathrm{w}}_{\mathrm{pf}}\mathbf{k}} \right|_{{}^{\mathrm{w}}_{\mathrm{tcp}}\mathbf{k} = \mathrm{const}} \tag{8}$$

where ${}^{\mathrm{w}}_{\mathrm{pf}}\mathbf{k} = {}^{\mathrm{w}}_{\mathrm{pf}}\begin{bmatrix} x & y & \alpha \end{bmatrix}^{\mathrm{T}}$ is the vehicles configuration and ${}^{\mathrm{w}}_{\mathrm{tcp}}\mathbf{k} = {}^{\mathrm{w}}_{\mathrm{tcp}}\begin{bmatrix} x & y & z & \delta_x & \delta_y & \delta_z \end{bmatrix}^{T}$ is the manipulator configuration in world coordinates that is assumed to be constant, since the TCP motion is decoupled from the platform motion. This gradient can be factorized into the following terms:

$$\mathbf{g} = \left. \frac{\partial c}{\partial\, {}^{\mathrm{w}}_{\mathrm{pf}}\mathbf{k}} \right|_{{}^{\mathrm{w}}_{\mathrm{tcp}}\mathbf{k} = \mathrm{const}} = \left. \frac{\partial c(\underline{\theta})}{\partial \underline{\theta}} \frac{\partial \underline{\theta}}{\partial\, {}^{\mathrm{tcp}}_{\mathrm{tcp}}\mathbf{k}} \frac{\partial\, {}^{\mathrm{tcp}}_{\mathrm{tcp}}\mathbf{k}}{\partial\, {}^{\mathrm{w}}_{\mathrm{pf}}\mathbf{k}} \right|_{{}^{\mathrm{w}}_{\mathrm{tcp}}\mathbf{k} = \mathrm{const}} . \tag{9}$$

The first term depends on the cost function and can easily be computed for the function from Eqn. (7). The following term is the inverse Jacobian of the manipulator $\mathbf{J}^{-1}$, the computation of which is done using an algorithm of [19]. Finally, the influence of differential platform motions to the TCP motion for the TCP resting in world coordinates is described. The velocity transformation from [20] is used to compute this matrix. The product of these terms results in an expression valuating differential platform motions in terms of the cost function. This algorithm can be applied to every manipulator on the platform.

5.2 CONFIGURATION CONTROL

When every manipulator configuration has been valuated using Eqn. (9), the desired vehicle velocity has to be computed. This results in a control loop for the manipulators configuration which is shown in Figure (8).

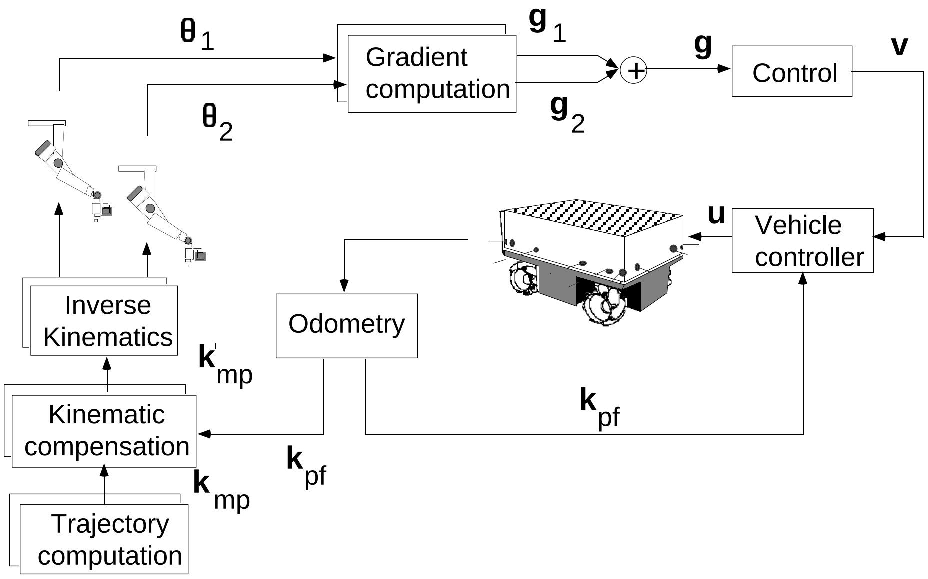

Figure 8: Control loop for the manipulator configuration

In the following, a first approach for the configuration controller is described. It is based on the concept of sliding mode control [21]. The gradient and its time derivative are used to define the sliding surface:

$$\mathbf{s}(t) = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\alpha} \end{bmatrix} - v(\mathbf{g} + T\dot{\mathbf{g}}) \frac{\mathbf{g}}{\|\mathbf{g}\| + \varepsilon}. \tag{10}$$

The constant v has to be experimentally chosen, as well as the time constant T. The small constant ε is introduced to reduce the chattering often found with sliding mode controllers. The sliding surface $\mathbf{s}$ is used to compute the control output, the cartesian acceleration **:**

$$\mathbf{a} = -\mathrm{a}_0 \frac{\mathbf{s}}{\|\mathbf{s}\|}, \tag{11}$$

where $\mathrm{a}_0 > 0$ is a finite acceleration. This acceleration is integrated to the vehicle's velocity and then given as a desired value to the vehicle controller, the explanation of which is beyond the scope of the paper.

5.3 EXPERIMENTAL VERIFICATION

In the following some simulation results are described which have been performed to evaluate the approach. The simulated system is identical with the mobile robot KAMRO introduced in section 1, i.e., it consists of two PUMA-type manipulators in a hanging configuration on a mobile platform with a holonomic drive system.

The Figures (9) show a simulated run with a given trajectory for the two manipulators and the resulting trajectory for the platform, as well as the cost function for both manipulators. The resulting trajectory for the platform shows that the described configuration control is appropriate to support one (Figure 9a) or more (Figure 9b) manipulators. The rectangles in the figures indicate the shape of the mobile platform after certain time intervals. The course of the cost functions shows that the supported manipulators can be kept near an optimal configuration after a transient process.

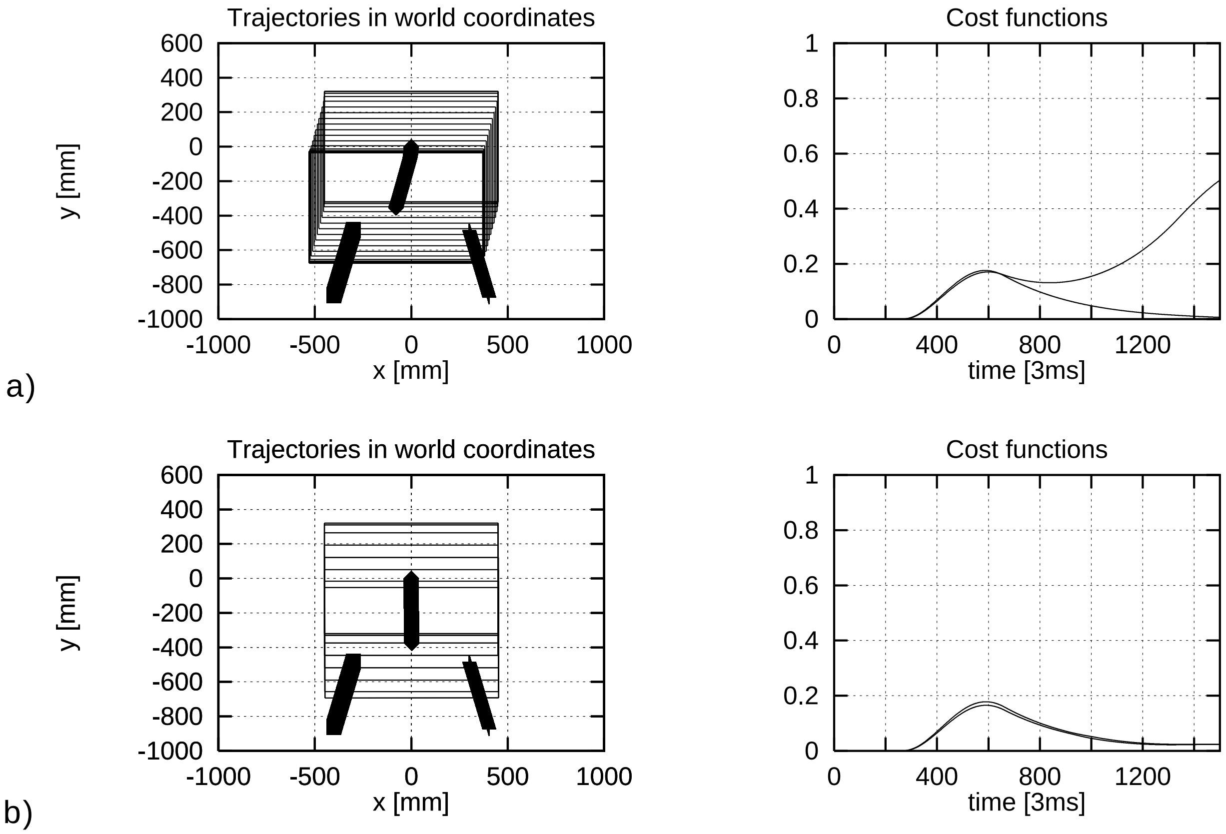

Figure 9: Trajectories in world coordinates for a) platform supporting only one manipulator b) platform supporting both manipulators

6 SUMMARY

On the area of autonomous mobile systems an increasing number of platforms with on-board manipulators can be found. In almost all cases the platform and the manipulators are considered as two separate systems. This article is concerned with the cooperation of manipulators and a mobile platform. After analyzing the possible applications for a cooperating manipulator-platform-system the principle methods for the cooperation are described and compared. We distinguish between the classes *loose cooperation*, *transparent cooperation* and *complete cooperation*. For the transparent cooperation, a concept is presented and the realization of the control level for an existing mobile two-arm system is described. Using this kind of cooperation, the workspace of the robot can be remarkably enlarged. Future work will deal with the dynamic properties of the system and with motion planning using a configuration space model.

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