KINEMATIC MODELING AND LOW-LEVEL MOTION PLANNING FOR REDUNDANT AND MOBILE ROBOTS

Summary of a Ph. D. Thesis by

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1 Introduction

Recent trends in robotics show the increasing application of kinematically redundant robots (i.e. ones whose degrees of freedom, DOF hereafter, transcend the workspace dimensionality), among them those which are composed of several robots, such as micro- and macro-manipulators or mobile robots consisting of a wheeled platform and an arm (referred to as mobile manipulators in recent literature).

In many cases, the application of kinematically redundant manipulators becomes necessary because of a cluttered or heavily obstructed environment (such as working inside cavities) where the conventional 6 DOF of an industrial robot may not suffice for collision-free work. Kinematic redundancy may also occur as a consequence if several components are integrated into one robot, as is the case with mobile manipulators. Here, a “conventional” manipulator is attached to a mobile base, thus combining the extended workspace of a mobile platform and the manipulation abilities of a robot arm. Regardless of the kinematic redundancy being either a desirable property or rather a consequence, the motion planning and control of redundant robots brings about a new problem. For a non-redundant robot, the desired workspace motion (in most cases the motion of the end point or tool center point, hereafter TCP) determines an unambiguous behavior in the robot’s configuration space (e.g. joint movement), while kinematic redundancy results in an infinite number of possible solutions, i.e. a solution space. Since only one of these can be applied to the robot, it becomes necessary to pick one of the possible solutions, in other words, an appropriate redundancy resolution method has to be applied.

Although this necessity may need additional work, it is also a key to exploiting the advantages of redundant robots over non-redundant ones, since the resolution method can pick a “most preferable” solution according to additional motion requirements, such as collision avoidance or a coordinated motion of arm and mobile base for a mobile manipulator.

Redundancy Resolution—Theory and Application

Redundancy can be represented in all three possible modeling approaches of robots, and solution methods exist for all three models. The most fundamental kinematic model describes the workspace position $x$ as a (usually nonlinear) function of the configuration variables $q$:

$$x = F_{\text{dir}}(q)$$

where the index of $F_{\text{dir}}$ stands for “direct kinematics.” It is clear that for a redundant robot, an infinite number of $q$ may exist for a given $x$. A general position algorithm for this problem was presented by Sezgin [21], where the robot’s nonlinear kinematic description is taken, together with a desired end point position (and orientation), as an optimization constraint (i.e. the end point requirement shall be always fulfilled), while secondary requirements may be included into an optimization criterion. This Lagrange-multiplier-based method can be applied to any open-chain rigid-link robot; the examples stated by Sezgin even demonstrate its applicability to a generalized case: several robots in close cooperation. For some specific cases, it may be of advantage if the redundant degrees of freedom are expressed in a separate, often suggestive set of variables. Dahm et al. [12] propose such a solution method for a specific 7-DOF manipulator, where a given end point position (and orientation) is prescribed again. This method transfers
the redundancy into one separate DOF, which can be parameterized later by an algorithm to complete the redundancy resolution.

The differential kinematic model of a robot describes the relation between workspace and configuration space velocities and can thus be regarded a local linearization of the kinematic model:

\[ \dot{x} = J(q) \dot{q} \]

where the configuration-dependent \( J(q) \) is the Jacobian matrix of the robot, containing the partial derivatives of \( F_{\text{dir}} \) with respect to the various components of \( q \). If the workspace is \( n \)-dimensional and \( q \) has \( m \) components, \( J \) is an \( n \times m \) matrix. The redundant case \( m > n \) results in an underdetermined set of linear equations where linear algebra techniques can be used to determine a desired solution. For this approach, most authors rely on gradient projection, as shown by Sezgin [21] and Žlajpah [24], where the solution is a sum of a minimum-norm particular part ensuring the correct workspace velocity, and a homogeneous part which has no effect on the workspace motion, since it is obtained by the projection of a configuration space velocity preference into the null space of \( J \):

\[ \dot{q} = \dot{q}_p + \dot{q}_h = J^+ \dot{x} + \alpha N_{\text{proj}} h \]

where \( J^+ \) is the Moore-Penrose pseudoinverse of \( J \), which ensures a minimal Euclidean norm \( \| \dot{q} \| \), \( N_{\text{proj}} \) is the projection matrix and \( h \) is a motion preference, usually the gradient of a virtual potential function. Though this method does not demand too much in computing costs, a major drawback is that no specific value can be guaranteed for any component of the configuration velocity vector, as would be required for handling critical situations. The “FSP” (full space parameterization) by Pin et al. [17, 14] offers a remedy to this shortcoming, since the most suitable \( \dot{q} \) is determined by constrained optimization. The optimization space \( \mathcal{E} \) is spanned by linearly independent solution vectors \( g_i \) to the differential kinematic equation, and a possible solution can be obtained with the weight vector \( t \) as their linear combination.

\[ \mathcal{E} = \left\{ \dot{q} \in \mathbb{R}^m; \quad \dot{q}(t) = \sum_{i=1}^{m-n+1} t_i g_i; \quad \sum_{k=1}^{m-n+1} t_k = 1 \right\}; \quad J g_i = \dot{x}; \quad i = 1 \ldots m - n + 1 \]

where the workspace has \( n \) dimensions and the configuration space has \( m \). The layout of FSP finds the \( g_i \) solution vectors by selecting a non-redundant subsystem (different for each \( g_i \)) with a square invertible Jacobian matrix and solving the inverse differential kinematic problem with the rest of the joint space velocities set to zero. The final solution is then found as a linear combination of the \( g_i \), through the optimization for the quadratic criterion

\[ \min_{\dot{q}} \frac{1}{2} \| B \dot{q} - z_r \|^2 \]

and optional constraints of the linear equality type

\[ \beta^T t - e_p = 0 \]

The optimum can be computed with a closed formula (as opposed to iterative optimization), which can make this method suitable for real-time application.
Another way of redundancy resolution on the differential kinematic level can be the extension of $J$ with extra rows (and augmenting the prescribed $\dot{x}$ with a corresponding number of extra elements), so that the extended matrix becomes square and invertible and a fully determined system of linear equations can be solved. This approach was proposed by Sciavicco et al. [20] as “workspace augmentation.”

The dynamic model is rarely included in redundancy resolution methods; at least for “local” approaches which solve only for one given step in a possible motion sequence. As an example, force-control methods of Žlajpah [23] should be mentioned.

As opposed to local methods, global planning procedures for pre-computed paths consider an entire motion sequence. This approach is of foremost importance for complicated motion tasks in cluttered environments, many of them envisaged for redundant robots. Departing from a local perspective, Schlemmer et al. [19] employed redundancy resolution in a planning framework for the entire motion sequence. Here, corner points of an interpolated motion are determined by semi-infinite optimization using the dynamic model. Another significant approach are the “elastic band” and related methods developed by Khatib et al. [16], also applied for the “Stanford assistant,” a mobile manipulator with an omnidirectional mobile base.

As for applications, the most common secondary motion requirements for redundancy resolution methods are related to collision avoidance of open-chain manipulators. These may range from simple virtual potential fields and virtual forces, computed via a geometric model of the environment [21], or contact forces from sensory input [23], to (possibly piecewise continuous) objective functions representing actual object boundaries and obstacle penetration measures [19, 16].

A special application of redundancy resolution concerns macro- and micro-manipulator systems and mobile manipulators where the key issue is the coordinated motion of the two subsystems, also taking their differing dynamic properties into account.

### Mobile Manipulators—Modeling and Control

Mobile manipulators, as referred to in recent literature, consist of a (mostly wheeled) mobile base and one or more manipulators mounted thereon. The purpose of this construction is the combination of the advantages of both robot classes: the manipulating abilities of the robot arm and the extended workspace of the platform. While conventional modes of operation (“stationary” manipulation and pure transport tasks) are still possible with these robots, the most important case is the simultaneous use of arm and mobile base.

As is the case with any other robot as well, a correct model in the key prerequisite for motion planning and control methods. An obvious way of obtaining a kinematic or dynamic model for a mobile manipulator is the combination of the already known and well-researched models of the two components, which, however, reveals two important facts. First, the only suitable models for most mobile manipulators can be either differential kinematic or dynamic ones, since nonholonomic mobile platforms cannot be fully described merely by their position and orientation. Second, the dynamic interaction of arm and mobile base should be introduced as a new element to the dynamic model. The latter problem has received an increasing focus in recent research, as shown by Yamamoto et al. [26], or Duleba [13].
In most cases, the manipulator already has sufficient number of DOF for all workspace tasks, therefore, the presence of the mobile base introduces redundant DOF. However, in addition to the most common secondary goals of redundancy resolution, additional care must be taken about a sensible *arm and base coordination strategy*. As shown by Yamamoto [25] or Grebäck [15], a “natural” strategy drives the platform along an (approximate) path which ensures a preferable configuration for the arm. This preference is mostly selected by the arm’s kinematic motion reserve [25], although other criteria, such as lowest potential energy can be applied as well [15].

In some cases, such as the Stanford assistant composed of an omnidirectional mobile base and a PUMA 560 arm, the dynamic properties of manipulator and platform do not show major differences and allow the entire system to be controlled in a “uniform” way, as described by Khatib et al. [16] using the dynamic model, or by Pin et al. [18] with differential kinematics. In other cases, however, difficulties may arise because of various properties of the mobile base:

- The platform is nonholonomic. In this case, such approaches as simple gradient techniques may fail due to the restricted mobility of the mobile base (e.g. if the platform cannot drive immediately sideways).

- The control bandwidth of the platform is much narrower than that of the arm.

- The motion of the mobile base is much less precise than that of the manipulator and may be subject to such disturbances as wheel slip, uneven terrain etc.

- The self-localization of the mobile base is less precise than the arm’s internal sensors and introduces by its nature (multi-sensor fusion) a significant time delay.

Yamamoto [25] addressed these problems and proposed a split-up motion planning scheme. Here, the key issue is a “natural” coordination strategy again, whose importance becomes clear in the light of the aforementioned circumstances: the mobile platform is only required to roughly approximate the desired path while the arm, kept in a configuration with sufficient motion reserve, performs the exact positioning and compensates possible motion errors of the platform. Yamamoto employs separate planners for both arm and platform and resolves hereby the kinematic redundancy of the entire system (note that this method, however, does not facilitate global requirements for the robot). In [25], also issues of control bandwidth differences and cases of dynamic interaction are addressed.
2 Scope and Goal of the Research Work

The research work presented in this PhD thesis is chiefly “application driven” (as opposed to “goal driven” research), since most of the work had to solve motion planning problems for one given mobile manipulator or its components. The properties of this specific hardware, especially the relatively low velocities, already outlined the scope of the research in some respect: the dynamic model was considered an overkill and thus, only differential kinematics of arm and mobile base were used. Within this framework, three groups of problems are addressed:

- kinematic modeling of a specific 8-DOF manipulator, giving a closed-form parameterizable solution for the inverse kinematic positioning problem and joint space maps for singularities and manipulability values;

- enhancement of already existing redundancy resolution methods for the inverse differential kinematic problem, introduction of a new algorithm and a comparison of the methods with respect to their abilities and symbolic properties;

- differential kinematic modeling of mobile manipulators with a unicycle-type mobile base, suggestions for construction preferences and an algorithm for arm and base coordination, employing the newly introduced redundancy resolution method.

3 Methodology and Appliances of the Research

The algorithms presented in this work were tested in simulation and with a physical system as well. For the “off-line” part of the work, both C code and MATLAB were used, the latter also making use of the Robotics Toolbox. Because of the application-driven nature of the work, the entire modeling of the mobile manipulator was, from the beginning on, implemented in C, along with the redundancy resolution algorithms and their embedding environment. Therefore, especially in later phases of the research, MATLAB and the Robotics Toolbox were only used for visualization of motion sequences or specific robot postures, and some quick diagnostic utilities, such as determining the motion reserve or the Jacobian matrix of the robot for a given configuration. The final simulation runs, using a kinematic model of the robot, were all carried out in a C-coded environment, before being transferred to the actual robot’s on-board hardware, while MATLAB was used for their visualization and off-line diagnostics throughout the practical tests.
The algorithms were finally tested on a physical robot. The experimental mobile manipulator was designed at Siemens Corporate Technology IC6 in Munich, Germany for experiments in service robotics, as a part of the MORPHA project sponsored by the German Federal Ministry of Education and Research [22]. Kinematically, the mobile manipulator consists of a unicycle-type mobile base (having two independently driven wheels with collinear axes and a passive castor wheel) and an 8-DOF manipulator in an RTR\textsuperscript{6} arrangement, equipped with a parallel-jaw gripper. The joints of the arm, the gripper, a movable pan/tilt “head” for camera support and the two driven wheels are actuated by electronically commutated DC motors which can be controlled for torque, velocity or position by autonomous modules; the necessary communication running through a CAN-bus.

The service robotic application, implying a partly unpredictable and constrained environment, necessitated a large number of external sensors. The parallel-jaw gripper is equipped with tactile arrays and opto-mechanical force/torque sensors, and to facilitate vision-based manipulation, a laser and a camera is also attached to the gripper module. Most segments of the manipulator (as well as the sides of the mobile platform) are equipped with tactile skin panels, while one laser scanner is used for contact-free exploration of the mobile platform’s environment and another laser scanner (along with a stereo camera) is attached to a pan/tilt module atop the arm and serves as a sensory “head” for manipulation tasks.

The robot is equipped with two on-board industrial PC’s running Linux, interconnected with an Ethernet segment. One PC is dedicated to vision, strategic level tasks and wireless communication with a stationary computer while the other PC carries out the low level motion planning tasks. Most of the results presented in this thesis found an application in the latter, being a substantial part of modeling, point-to-point motion and workspace motion functionalities.
4 Summary of New Results

Thesis Group 1

I have generalized the redundancy handling algorithm of Dahm et al. [12] for the case of an 8-DOF robot which also contains a prismatic joint. I have developed a systematic method to find the manifolds of singular configurations. Publications covering this topic: [8, 9, 11].

1.1

The generalized redundancy handling algorithm expresses the manipulator’s redundancy with two suggestive parameters: a “virtual elbow angle” and the position of the prismatic joint. These two variables strongly affect the manipulability measure; therefore, I have developed a manipulability map for their adequate real-time determination. Using simple rules, the algorithm allows the early indication and avoidance of the robot’s collision with its own segments. I have shown that the positioning part of a full position and orientation task can be further decomposed if one of the first two joints is revolute and the other is prismatic, while their axes are collinear. In this case, the manipulability map determining the advantageous virtual elbow and prismatic joint values has only one independent parameter.

1.2

Based on a geometric/kinematic perspective, I have proposed a classification of a given 8-DOF arm’s singularities.

a) In the first group of singular configurations, the first 5 joints of the arm do not guarantee a full three-dimensional motion reserve for the linear velocity. I have presented a method which determines the specific directions in Cartesian space, along which the motion reserve can be exhausted. I have shown that 4 independent manifolds exist for the singularities caused by the first 5 joints.

b) The second group of singularities contains the cases where the “wrist” is singular. A dimension loss in the rotatory motion reserve of the last 3 joints does not imply the singularity of the entire robot (as opposed to non-redundant manipulators), since a revolute joint of the proximal five joints could still recover the lost dimension of motion reserve. I have given a two-step constructive method for the determination of such cases. I have proved that for a singular configuration of the last 3 joints, 6 separate configuration manifolds exist, for which the entire arm is singular.

Thesis Group 2

I have proved that the FSP (Full Space Parameterization) algorithm proposed by Pin [17] for the inverse differential kinematic problem of redundant (mobile or non-mobile) robots returns critical results in specific cases, and I have presented further improvement of the method for such cases. I have proved that the FSP method can be—without a significant increase of computing costs—decomposed to an unconstrained solution and a correction term enforcing the
I have developed a new algorithm (PNS, Parameterization through Null Space) for the optimization problem handled by FSP which is numerically more robust than FSP and has a modular structure. I have set up a new method for the local motion planning of redundant robots which keeps the robot near a preferred configuration during motion and ensures continuous acceleration even upon encountering joint limits. Publications covering this topic: \[1, 2, 3, 5, 6, 7\].

2.1

I have proved that the FSP-method of Pin \[17\] is affected by numerical problems in two cases. I have presented new solutions to overcome both types of problems:

a) I have proved that in its original layout, the numerical robustness of FSP can be also impaired if the robot—as a whole—is far from singularities yet one of the selected sub-systems is nearly singular and the norm of the corresponding g solution vector becomes dominant. This imposes numerical difficulties on further optimization steps. To avoid this shortcoming, I have extended the original FSP by a rescaling step which diminishes the critical configuration areas susceptible to the above failure.

b) I have proved that FSP is, in its original form, unable to handle zero end point velocity commands (which does not imply zero joint velocity for redundant robots). To circumvent this problem, I have given a new solution space for zero velocity commands which composes the null space of the robot’s Jacobian matrix J with solution vectors \( g \) obtained for a fictitious nonzero prescribed velocity:

\[
\mathcal{N} = \left\{ \dot{q} \in \mathbb{R}^m : \dot{q}(t) = \sum_{i=1}^{m-n+1} t_i g_i; \sum_{k=1}^{m-n+1} t_k = 0 ; \ J_{g_i} = \dot{x} ; \ i = 1 \ldots m-n+1 \right\}
\]

For the application of the modified FSP algorithm, I have developed a method for switching over at zero/nonzero velocity command boundaries.

2.2

I have proved that it is possible to split up—without a significant raise in computing costs—the optimization algorithm of FSP to an unconstrained optimum and a correction term whose addition to the unconstrained part ensures the constraints. I have presented a new layout of FSP according to this decomposition and demonstrated its importance for cases where the robot performs a motion series near a danger zone whose handling necessitates constraints.

2.3

I have developed a new method (PNS, Parameterization through Null Space) to solve the inverse differential kinematic problem of redundant robots. The new method solves the optimization problem already addressed with FSP, however, the more robust PNS does not encounter the numerical problems of FSP. The method’s modular structure allows further enhancement as well. I have developed an extended version of PNS which includes additional surveillance and handling of singularities without a noteworthy raise of computing time.
PNS obtains the solution, similarly to gradient projection, as the sum of a particular term $\hat{q}_p$ and a homogeneous term $\hat{q}_h$:

$$\hat{q} = \hat{q}_p + \hat{q}_h; \quad J\hat{q}_p = \dot{x}; \quad J\hat{q}_h = 0;$$

The minimum-norm particular part of the form $\hat{q}_p = J^+ \dot{x}$ is calculated using the Moore-Penrose pseudoinverse of the Jacobian matrix, while the homogeneous part is a linear combination of the null space base vectors to $J$, optimizing a criterion given for the entire solution and complying with the constraints, also set for the entire solution. The pseudoinverse and the null space base vectors are obtained with the singular value decomposition (SVD), as shown in Fig. 2, delivering as a by-product the scalar manipulability measure for the given configuration, calculated as the product of singular values.

![Figure 2: Schematic structure of PNS](image)

The criteria and constraints used by PNS are defined for the entire solution ($\hat{q} = \hat{q}_p + \hat{q}_h$), and are identical in form to those used with FSP:

$$Q = \frac{1}{2} \| B\hat{q} - z_r \|^2 = \frac{1}{2} \| B(\hat{q}_p + Nt) - z_r \|^2; \quad \beta^T t - e_p = 0$$

I have proved that the optimization performed in PNS can be executed by a closed formula. In the split-constraint decomposition I have already introduced for FSP, the optimization in PNS consists of the following steps:

I. Unconstrained optimum:

$$G := N^T B^T B N \quad H := N^T B^T B\hat{q}_p - N^T B^T z_r \quad t_{unc} := -G^{-1} H$$

II. Correction term to enforce the constraints:

$$d := e_p + \beta^T G^{-1} H = e_p - \beta^T t_{unc} \quad A := \beta^T G^{-1} \beta \quad \nu := -A^{-1} d \quad t_{corr} := -G^{-1} \beta \nu$$
The solution is then comprised of the following:

\[ \dot{q} := \dot{q}_p + N(t_{unc} + t_{corr}) \]

The method avoids the aforementioned problems of FSP, since it can handle zero velocity commands and it is not sensitive to near-singular subsystems. I have shown that due to the application of SVD, the condition numbers encountered in the optimization part of PNS are much better than those in FSP; therefore, even those configuration areas can be approached with more safety where the properties of the entire robot deteriorate.

I have augmented PNS with a new function which cannot be built into FSP. The extension allows an easy handling of singular configurations without noteworthy raise in computing costs. In this method, those singular values of the Jacobian matrix are inspected which do not belong to the null space of \( J \). Since the pseudoinverse \( J^+ \) is calculated using the reciprocals of these singular values, they are kept above a predefined limit by a quadratic function if they would sink below a given threshold. This ensures that no component of the joint velocity transcends a given value while joint acceleration remains continuous in time.

I have proved that gradient projection is equivalent to a special case of optimization where \( B \) of the quadratic criterion is an identity matrix and the reference vector for the joint space motion preference is \( z_r := \alpha h \). Thus, the optimization-based FSP and PNS methods can be considered a generalization of gradient projection where departure from \( B = I \) means the non-uniform weighting of the joint velocity components (if \( B \) is diagonal) or an arbitrary linear transformation of configuration space (any \( B \) which does not cause rank loss), while optimization constraints of the linear equality type can be prescribed as a further extension possibility.

I have developed a new algorithm for the local motion planning of redundant robots which—utilizing FSP or PNS—executes a given Cartesian motion command and brings/keeps the robot near a preferred configuration. The method guarantees continuous joint acceleration in time and is also able to handle joint limits.

a) For driving the robot towards a preferred configuration, I have developed a solution using a control engineering principle. To each component of the joint velocity vector, a fictitious control loop is assigned where the difference between preferred and actual configuration is treated as a control difference and the controller output is the corresponding component of the \( z_r \) reference vector in the quadratic criterion (see Fig. 3).

b) For joint limit surveillance and handling, I have developed a new scheme which determines the modification of the unconstrained joint motion with the introduction of constraints in the optimization. The surveillance strategy can be expressed in a rule base which checks the following condition for the components of joint space to be kept track of:

\[ ((\dot{q}_i < 0) \land (q_i < q_{i,v})) \lor ((\dot{q}_i > 0) \land (q_i > q_{i,h})) \]
where $q_{i,l}$ is the upper limit of the danger zone assigned to the lower end of the joint range while $q_{i,h}$ is the lower end of the upper danger zone in an analogous way. Should such a condition apply for a joint, its original unconstrained velocity is scaled down by a quadratic function which keeps the joint from leaving its permitted range, while joint acceleration remains continuous in time. The complete scheme of the motion planning algorithm, including controllers and rule base, can be seen in Fig. 4.

Figure 3: Controllers for approaching a preferred configuration

Figure 4: Scheme of the complete motion planner

Thesis Group 3

I have developed a differential kinematic model for mobile robots consisting of a unicycle type mobile platform and an arm mounted thereon, which also includes the nonholonomic constraints. Therefore, the model guarantees that the constraints do not have to be taken into account separately while solving the inverse differential kinematic problem. Using this model, I have determined the most advantageous placement of the arm’s base with respect to the coordinated motion of arm and mobile base. I have developed a new two-step algorithm for the arm-base-coordination which allows the definition of global motion criteria for the entire robot, yet it also takes the differing properties of arm and mobile base into account. Publications covering this topic: [2, 3, 4].
3.1

I have derived a new differential kinematic model for an important class of mobile robots, comprised of a unicycle type wheeled mobile base and an \( m \)-DOF arm. The model unifies the description of the manipulator (\( \dot{x} = J(q_{arm}) \dot{q}_{arm} \)) and that of the mobile base (\( \dot{q}_{base} = S(q_{base}) u \)) by adding further columns to the arm’s Jacobian matrix which already take the nonholonomic properties of the mobile base into account. For the Cartesian motion of the arm’s end point (in its own frame) the following model was thus obtained:

\[
\begin{bmatrix}
  m \dot{v}_{m} \\
  m \omega_{m}
\end{bmatrix} = \begin{bmatrix}
  \begin{bmatrix}
    1 \\
    0 \\
    0
  \end{bmatrix} & \begin{bmatrix}
    -y_{b} - y_{m} \\
    x_{b} + x_{m}
  \end{bmatrix} \\
  R_{0,m}^{T} & R_{0,m}^{T} \\
  0 & 0
\end{bmatrix} \begin{bmatrix}
  \dot{q}_{1} \\
  \dot{q}_{m} \\
  \eta_{1} \\
  \eta_{2}
\end{bmatrix},
\]

where \( \eta_{1} \) is the linear velocity of the mobile platform, \( \eta_{2} \) is the angular velocity, while \( v_{m} \) and \( \omega_{m} \) are the linear and angular velocities of the end point, respectively. The upper left index denotes in which frame the given expression is interpreted, \( R \) is the orientation part of the homogeneous transformation referred to in the lower right index. The meaning of the variables is also shown in Fig. 5.

![Figure 5: Schematic layout of a mobile manipulator](image)

I have derived two important consequences of the above model:
a) I have proved and demonstrated through practical realization, that local motion planning can be carried out without relying on the (usually less precise and lagging) self-localization of the mobile base.

b) I have proved that the “natural” arm-base-coordination principle can exploit the kinematic reserve of the mobile base to the highest degree if the base of the manipulator is not mounted above the common axis of the platform’s differentially driven wheels (i.e. the y-axis of the usual platform frame), since any point above this axis loses a dimension of mobility.

3.2

I have developed a new algorithm for the local planning of the simultaneous coordinated motion of arm and mobile base. The two-step procedure allows the introduction of motion criteria for the entire robot, but it also takes different properties of arm and mobile base into account. One step of the method consists of a “platform cycle” wherein an “arm cycle” is performed once or multiple times, as required by control bandwidth differences between arm and platform. The algorithm first plans the motion of the entire mobile robot (locally, for the current motion step), then it determines the velocity command for the platform’s own differential controller. Hereafter, expecting a relatively “sluggish” platform motion, the arm velocities are corrected (once or multiple times within a platform cycle) taking into consideration the actual platform velocities. The schematic structure of the algorithm is shown in Fig. 6.

5 Application of the Results

Within the framework of a DAAD-scholarship (and later a contract with Siemens AG), I received the opportunity for a practical application of my theoretical results developed at the Department of Control Engineering and Information Technology of the Budapest University of Technology and Economics. From a control engineering point of view, my task was the real-time realization of an intermediate layer between the higher strategic level and the lower servo level.

The greater part of the results was directly applied for the Cartesian motion functionalities of the experimental mobile manipulator at Siemens Corporate Technology in Munich, Germany. These include point-to-point motion (straight-lined in configuration space) based on the inverse kinematic solution and straight-lined motion in Cartesian space for arm-only mode and simultaneous use of arm and platform as well. The test runs involving the FSP/PNS-based redundancy resolution methods included benchmark tasks of service robotics in “everyday environments,” such as sensor-guided door opening with arm and base coordination or object handling with tactile interaction. An example is shown in Fig. 7 where the mobile manipulator opened a door using tactile feedback of the motion error instead of relying on the mobile platform’s localization.

The research results were also published in international conferences and were partly included into the research programs OTKA T029072 and OTKA T042634.
Figure 6: Scheme of the arm-base-coordination method
Figure 7: A benchmark task: sensor-guided door opening
Publications on the Topic of the Thesis


Other References


