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Concepts for a Sensor-Guided Redundant Heavy Manipulator

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Abstract

The concept of a redundant heavy manipulator is presented which utilizes innovative techniques from the fields of mechanical design, control and sensors. The goal is the development of an easy-to-use tool performing complex tasks in a constrained workspace.

1. INTRODUCTION

Nowadays, commercial heavy manipulators are mostly derived from conventional excavators or mobile cranes. They are equipped with simple control devices, which results in complicated and time consuming operation for a manipulator with six degrees of freedom (DOF). Moreover, if the manipulator is used in a constrained environment, six degrees of freedom may not offer enough dexterity. Because of this, additional degrees of freedom are necessary, but such a redundant manipulator can hardly be operated by the simple control techniques mentioned above.

In the course of a mechatronic project in collaboration with industrial partners, a new type of heavy manipulator will be developed, which is intended for handling payloads of about 500 kilograms. Due to the frequently changing location, which results in unforeseeable workspace conditions, this new type of heavy manipulator has to be provided with manual control. Instead of the usual control of single joints a new manual control system for Cartesian guidance will be implemented, which relies on automatic subordinate control strategies to take advantage of redundancy.

If the manipulator works in an environment nearly free of obstacles, its redundant DOF will be automatically determined using suitable constraints. In the case of a workspace strongly constrained by obstacles, the user has to be able to control specific parts of the kinematic structure or even single joints. Such substructures consisting of up to six DOF can again be treated as manipulators to execute rough or fine positioning. In the next step, additional sensors will be introduced to automate the motion of the kinematic chain depending on the manually controlled tool motion. A set of suitable range sensors attached to the manipulator links measure the distance to obstacles located in the vicinity for the purpose of collision avoidance under real time conditions.

It is planned to build a fullscale prototype manipulator in collaboration with an industrial partner to realize the concepts described above under realistic conditions. Preliminary tests will be performed with a redundant SCARA robot with four revolute joints arranged in parallel.

2. DEVELOPMENT OF A REDUNDANT HEAVY MANIPULATOR

2.1. Design of the manipulator

In order to allow complex movements in a limited and unstructured environment it is necessary to equip the manipulator with redundant DOF. Ball joints which allow spatial adjustment of the rotation axis (Fig. 1) are integrated in the manipulator to reduce the number of joints without changing the number of DOF. Under ideal conditions one ball joint can replace three revolute joints, resulting in substantial reduction of the size and weight of the manipulator.

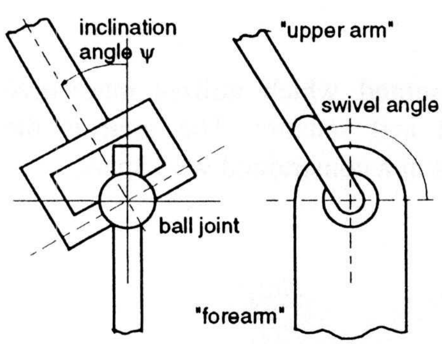

Figure 1: Mobility of a ball joint

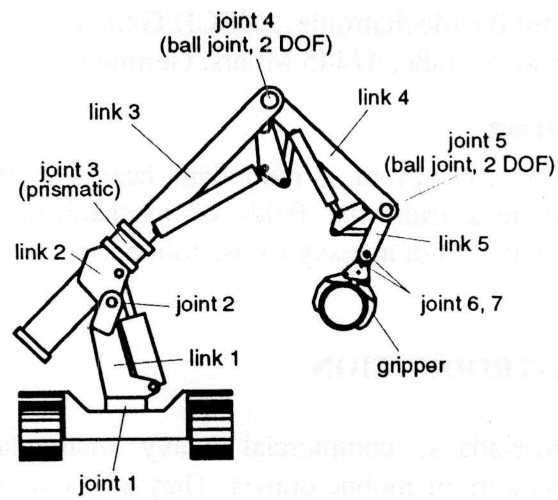

Figure 2: Structure of the redundant manipulator

The kinematic structure of the manipulator is essentially that of an elbow manipulator, but using two ball joints as elbows (Fig. 2). The ball joints are supposed to allow a swivel motion of at least 130° and an inclination of the rotation axis of ±30°. A spatial transmission linkage is necessary for controlling the movement of the ball joint, since the swivel angle exceeds 90°. The sub-assembly consisting of a ball joint and the respective transmission linkage will subsequently be called a ball-joint-unit.

A tracked vehicle will be used as base of the manipulator in order to move in unstructured terrain. Safety against overturning is achieved by sufficient vehicle-mass and additional outriggers.

2.2. Design of the ball joint transmission linkage

The first design was based on a planar transmission linkage used in existing large manipulators (Wanner 1990). Additional hydraulic pistons and ball joints instead of self-aligning bearings were supposed to allow spatial motion and adjustment of the rotation axis (Fig. 3). This adjustment of the rotation axis with two hydraulic pistons on the side of the arm was seen to occupy too much space. Using only two DOF saves one piston, but this must be replaced by a rod.

In order to design a symmetric ball-joint-unit, a solution using only two of the three possible DOF was found. The joint is driven by two parallel pistons which produce a planar motion by synchronous stroke of the pistons, while the adjustment of the joint axis is controlled by differential stroke. Studies of the transmission behaviour, the mobility and the internal forces in the mechanisms will be presented in detail.

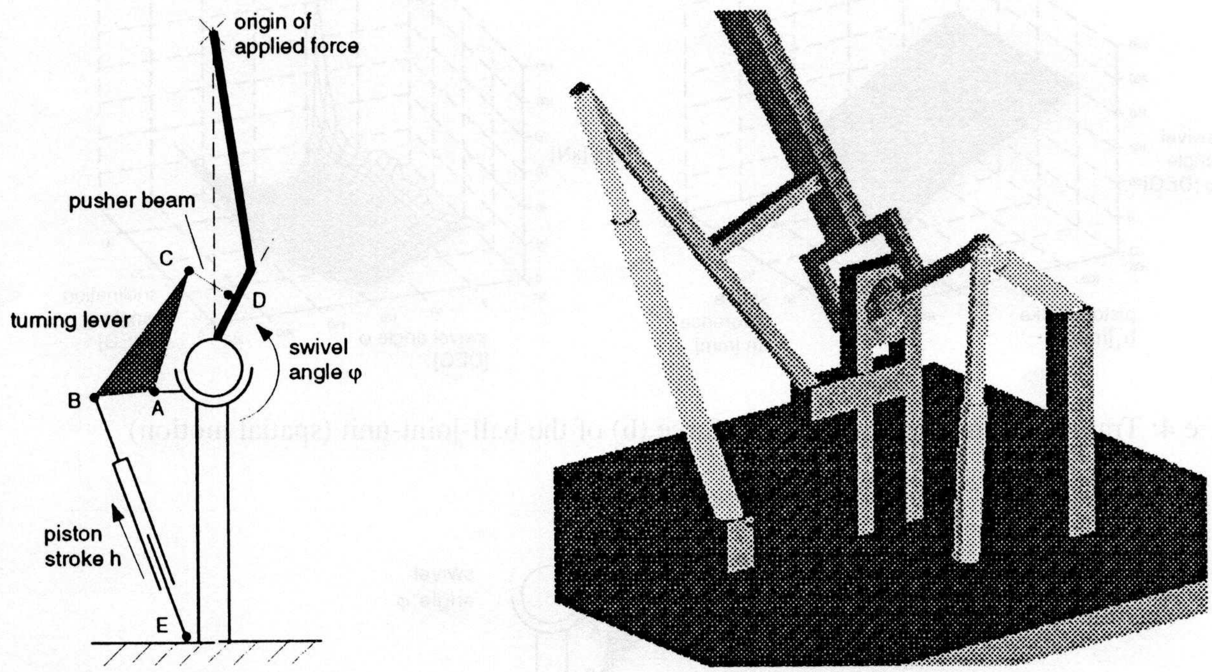

Figure 3: Transmission linkage for a ball joint with three DOF

The behaviour of the transmission linkage must be determined and evaluated with special regard to the development of a controller. The parameters h_1 and h_2 will denote the piston stroke, and the differential stroke $\Delta h = h_2 - h_1$. The relation between the orientation of the joint and the piston stroke is of primary interest: Fig. 4 shows the swivel angle as a function of the piston stroke and the differential stroke, in which $\Delta h = 0$ represents the planar case. The relationship between h_1 and φ is approximately linear over a wide range, and nonlinearities are evident only in the border areas. The differential stroke Δh only has a small influence on the swivel angle and the dependency of the inclination angle ψ on h and Δh is similar.

In the vicinity of singular positions (see e.g. Fig. 5) a high sensitivity of the forearm position with respect to changes of the stroke is noticeable. Therefore the geometric parameters have to be optimized in such a way that the working range of the ball-joint-unit is shifted into the linear area. This also reduces the forces occuring in the ball-joint-unit, because the high force gradients in the neighbourhood of singularities are avoided (Fig. 4). Although swivel angles of 180° are possible from the kinematical point of view, the resulting forces in the ball-joint-unit imply a limit of 150° when handling moments up to 10^4 Nm. The inclination angle is limited to ±30° due to the same reasons.

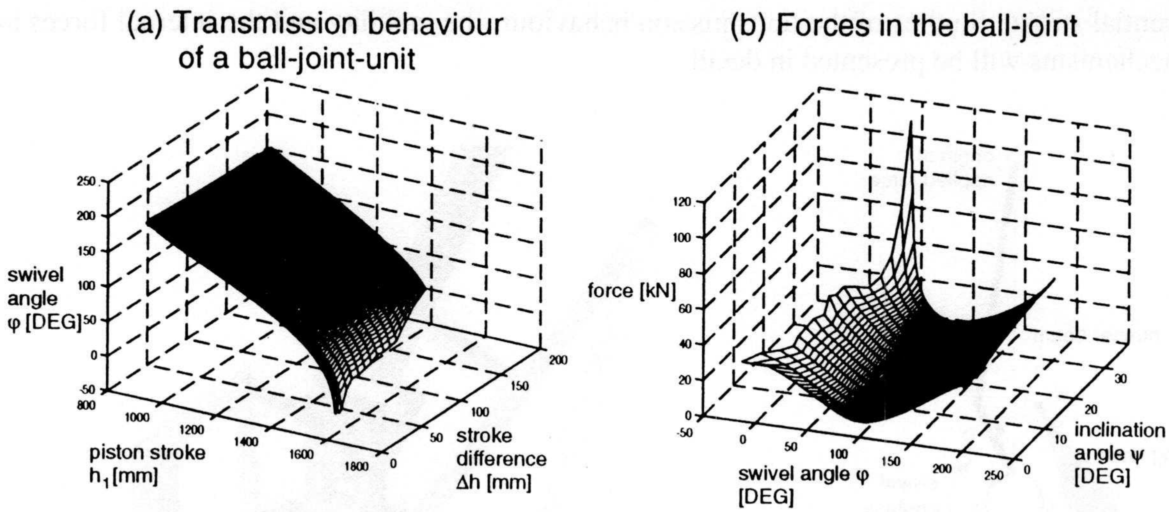

Figure 4: Transmission behaviour (a) and force (b) of the ball-joint-unit (spatial motion)

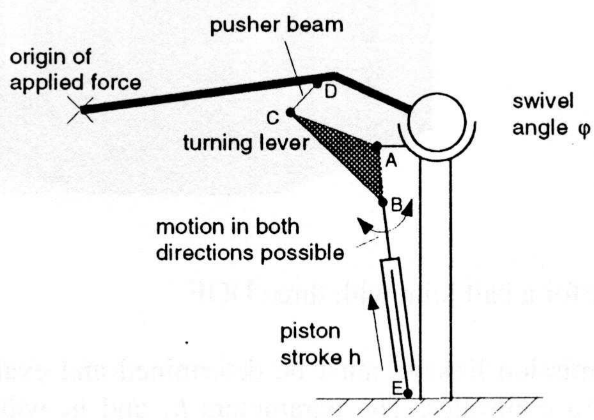

Figure 5: Example for a singular position of the transmission linkage

2.3. Kinematic analysis of the ball-joint-unit

Two three-axis control-levers are available to the user for Cartesian control of the manipulator with $n = 9$ DOF, allowing him to prescribe position as well as orientation. The manipulator will be controlled on the velocity level as described in the next section, where the relation between position and orientation of the end-effector $\underline{x} = (x,y,z,\Phi,\Theta,\Psi)^T$ and the joint variables $\underline{\theta} = (\theta_1,\ldots,\theta_n)^T$ is described with the help of the JACOBIAN in the form

$$\dot{\underline{x}} = \boldsymbol{J}\dot{\underline{\theta}} \ . \tag{1}$$

For a given motion $\dot{\underline{x}}$ one can find a particular solution to this underdetermined system of equations to obtain the joint velocities $\dot{\underline{\theta}} = (\dot{\theta}_1,\ldots,\dot{\theta}_n)^T$. The pair of joint angles θ_i and θ_{i+1} belonging to a ball-joint-unit j will be represented as a vector $\underline{\alpha}_j = (\theta_i,\theta_{i+1})^T$ in the following. Note that θ_i and θ_{i+1}, which describe the ball-joint-unit's two independent physical way of motions, are not equivalent to the angles φ and ψ described above. For the purpose of control one must compute the inputs $\underline{q} = (h_1, \Delta h)^T$ for the hydraulic actuators from these joint angles of each ball-joint-unit and, because control takes place on velocity level, one needs the relationship between $\dot{\underline{\alpha}}_j$ and $\dot{\underline{q}}$. Therefore, constraint equations are formulated for each transmission linkage in the form

$$\underline{g}(\underline{\beta}_j, \underline{\alpha}_j) = \underline{0}\,, \tag{2}$$

where the inputs h_1 and Δh are part of the dependent coordinates $\underline{\beta}_i = (\beta_1, \ldots, \beta_k = h_1, \beta_{k+1} = \Delta h, \ldots)^T$. Using the method described by Woernle (1988), these constraints can be efficiently solved for the dependent coordinates including the inputs for the hydraulic pistons. Corresponding solutions for the velocities are also easily formulated. At this point the inverse kinematic of a ball-joint-unit is known and can be integrated as a part of the control mechanism.

3. CONTROL CONCEPT

The movement of manipulators along simple Cartesian trajectories generally leads to simultanous changes in the DOF of the manipulator. Therefore it is desirable to support the operator in his complex control task. Due to the frequently changing location of the manipulator which results in unforeseeable workspace conditions, a fully automatic operation is impossible. Instead, a manual control system with subordinate control systems and other functionality not found in conventional systems will be developed as a part of the project. The core of the manual control system are two three-axis levers of which the first lever controls the motion of the end-effector, whereas the second lever prescribes its orientation. The concept of the control system must take into account the redundancies of the system, as the conversion of given values for position and orientation into joint coordinates is not unique. Depending on the task to be performed various control strategies utilizing different forms of inverse kinematics are applied to support the operator.

3.1. Inverse kinematics

For manual operation velocity proportional control is an obvious solution, since it guarantees safe operation and is easy to handle. Further, in contrast to position control the relationship between desired values in Cartesian and joint coordinates is linear. The connection between the *m*-dimensional workspace and the *n*-dimensional space of the joint coordinates on velocity level is given by the *n* x *m* JACOBIAN in the following form:

$$\dot{\underline{x}} = J\dot{\underline{\theta}}\,. \tag{3}$$

For the redundant heavy manipulator presented in this paper there are $n = 9$ joint coordinates as opposed to the $m = 6$ required DOF for position and orientation of the end-effector. There are thus $n - m = 3$ redundant DOF and Eq. (3) is an underdetermined linear system of equations for the inverse kinematics, for which no unique solution exists. Using a *generalized inverse* $J^{\#}$ (see e.g. Rao and Mitra 1971), the solution may be written in the form

$$\underline{\dot{\theta}} = J^{\#}\underline{\dot{x}}. \tag{4}$$

If we use the so-called pseudoinverse or MOORE-PENROSE-inverse $J^{\dagger} = J^{T}(JJ^{T})^{-1}$ this leads to the minimum-norm solution vector. This solution corresponds to a balanced activation of all DOF and is suitable under most conditions, but sometimes one needs a specific solution in order to avoid singularities or stay within joint limits. Such a special solution may be obtained by adding a *homogeneous* solution

$$\underline{\dot{\theta}}_h = \left(I - J^{\#}J\right)\underline{\dot{\phi}} \tag{5}$$

to the *particular* solution from Eq. (4). While the particular solution converts the desired velocities of the end-effector $\underline{\dot{x}}$ to joint velocities $\underline{\dot{\theta}}$, the homogeneous solution corresponds to a projection into the nullspace of the JACOBIAN. This means that for an arbitrary vector $\underline{\dot{\phi}}$ the corresponding homogeneous joint velocities $\underline{\dot{\theta}}_h$ have no influence on position and orientation of the end-effector, although they affect the configuration of the manipulator. So one can use $\underline{\dot{\phi}}$ to fulfil certain additional constraints or performance criteria, e.g. to remain within joint limits (Liégeois 1977).

3.2. Presence of obstacles

In case the workspace is restricted, the operator must be able to move specific joints or substructures. In this way the behaviour of a conventional elbow manipulator can be generated by blocking the second elbow and one more DOF in the outer part of the kinematic chain, which is sufficient to get close to the goal. For precise positioning near the goal a six DOF manipulator on a rigid boom can be obtained by blocking three DOF near the manipulator base. In addition, it may be required to control single joints without changing position and orientation of the end-effector in order to correct the kinematic chain in the vicinity of obstacles.

3.3. Use of external sensors

In the next step the movement of the kinematic chain during manual control of the end-effector will be controlled with help of external sensors. For this purpose a number of range detectors such as ultrasonic or radar sensors will be mounted on the links to measure the distance to obstacles. When an obstacle is detected in the vicinity of a point $\underline{x}_{ob}$ a particular solution is formulated in the null-space as described above to move away from the obstacle while maintaining the end-effector pose. The vector $\underline{\dot{\phi}}$ of Eq. (5) is computed from the JACOBIAN J_{ob} of the endangered point and used to formulate the vector of homogeneous joint velocities $\underline{\dot{\theta}}_h$ (Maciejewski and Klein 1985). Another method, based on a dynamic model, uses so-called virtual forces calculated from sensor data, which cause a repulsion from the obstacles (Khatib 1986).

4. EXPERIMENTAL PLATFORM

At present a planar SCARA-robot with four parallel axes is being developed to test the control strategies for redundant manipulators presented in Section 3 on an experimental platform. This robot has one redundant DOF for specified position and orientation of the end-effector, so that additional mobility is available for operation in a constrained workspace (Fig. 6). The manipulator is equipped with ultrasonic sensors, which give information about obstacles in the vicinity. On this basis strategies for collision avoidance can be implemented and tested.

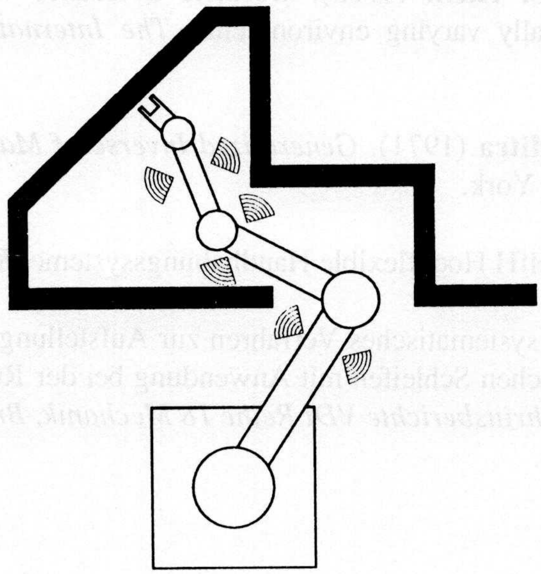

Figure 6: Experimental setup for a SCARA robot with four axes

5. CONCLUSIONS

Methods for automation in handling heavy loads in the construction industry as well as other areas are increasingly gaining in importance. Key aspects in the future will be the man-machine interface and the interaction with the workspace environment, which require highly integrated hardware- and software-concepts. Thus, a mechatronic approach to development is necessary. The concept of a sensor-guided redundant heavy-load manipulator presented here addresses such requirements. Important elements are cartesian control techniques and the exploitation of redundant DOF in combination with sensor integration for collision avoidance .

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