Concepts of an Advanced Cartesian Control System for a Redundant Twin Boom Drill Rig

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ABSTRACT

The handling of complex machines such as redundant manipulators requires appropriate control systems in order to make the operating of the system easier and to reduce processing time. This paper presents an advanced control system for a drilling rig used in tunnel construction which is currently under development in cooperation with an industrial partner. The drill rig is equipped with two redundant drilling booms each actuated by eight hydraulic drives. The main objective of the project is the improvement of manual handling of the redundant drilling booms. For this reason, a Cartesian control concept based on a special kind of the generalized inverse Jacobian is used to calculate in real-time the inverse kinematics on velocity level. Furthermore, collision avoidance strategies will be implemented to achieve real-time collision avoidance while operating the two booms at the same time. Another important aspect is the development of a graphically supported man-machine-interface which enables an easy handling in manual and automatic control modes.

1 INTRODUCTION

In the field of tunnel construction and mining industry drilling is an important task to perform drill and blast or bolting operations. Because the drill and blast method accounts for more then 75% of rock volumes excavated underground, the economic importance of efficient machines for drilling becomes evident. Therefore, a wide range of drill rigs has been developed, to accomplish the demands for production rates and mechanization from coal mining up to road tunnel construction. The available types of drill rigs extend from simple pneumatic or hydraulic drilling machines up to computer controlled electro-hydraulic drill rigs. The latter are able to produce drill patterns automatically, which are programmed off-line. This method is difficult to handle because the position of the drill rig has to be referenced with high accuracy to obtain exact hole positions what is important for the succeeding blast operation. Hesselbach and Nicolaysen (1995) describe a partially automated drill rig with five degrees of freedom which is able to perform Cartesian motions to support the operator and to enable faster working cycles.

In the following an advanced Cartesian control concept for a redundant twin boom drill rig is presented. The essential part of the Cartesian controller is a real-time algorithm for the calculation of the inverse kinematics of redundant systems, that means systems equipped with more than six degrees of freedom. This enables the operator to move the drill through Cartesian space without thinking about right positioning of the eight hydraulic actuators of the boom. This technique can even be used in automatic operation. Additionally, a real-time collision avoidance is implemented to prevent collision between movable parts of one boom or between parts of the two booms in arbitrary positions. Another important part of this project is the design of a new man-machine-interface which is necessary for an easy handling of these robotized actions. The aim is to give all possible support to the operator, which results in a significant speed-up of task duration, but not to replace him by a fully automated process, because this seems to be too complex in such hazardous environments and hence not economic.

The Cartesian control concept is just under development using a simulated model of the drill rig. Simultaneously, a full scaled test-bed for one redundant drilling boom including control system and man-machine-interface will be build up.

In section 2 the drill rig and a kinematic model for one of the drilling booms is introduced. The Cartesian control concept (section 3) which is based on inverse kinematics on the velocity level is described. Furthermore, section 4 discusses a collision avoidance strategy. The structure of the motion control system is presented in section 5. It consists of the man-machine-interface, a path generator containing the inverse kinematics and feedback controllers for the hydraulic actuators. Section 6 deals with a new concept of a man-machine-interface.

2 KINEMATIC MODEL OF THE DRILLING BOOM

The drill rig under investigation is a twin boom system used in tunnel construction (INTEROC tunnel jumbo). The machine is illustrated in Fig. 1. Nowadays, just simple manual control systems based on direct manipulation of the hydraulic valves are available.

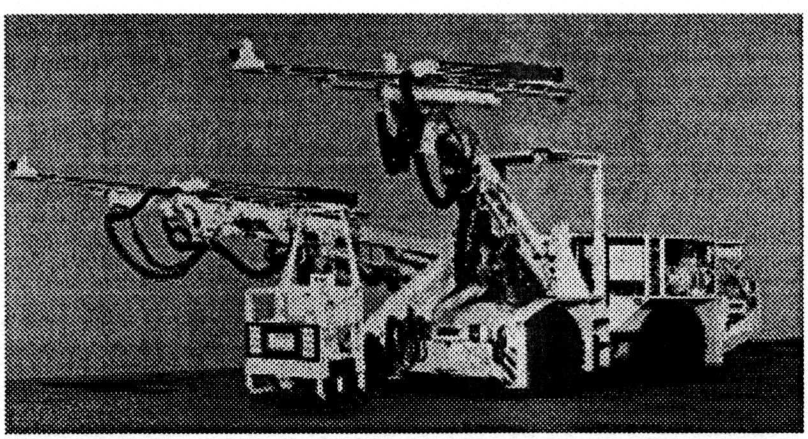

Figure 1: Drill rig equipped with two redundant drilling booms (INTEROC Germany)

To develop a Cartesian control concept a kinematic analysis of the considered system is necessary. The pure kinematic structure of the drilling boom without the actuator kinematics is shown in Fig. 2. The arrangement of the boom elements forms an open kinematic chain consisting of six revolute joints and two prismatic joints. The sum of the number of joints equals the number of degrees of freedom (DOF). Thus the drilling boom has 8 DOF. The joint coordinates which correspond to angles and displacement are denoted by the joint vector $\boldsymbol{\theta} = [\theta_1, \ldots, \theta_8]^T$.

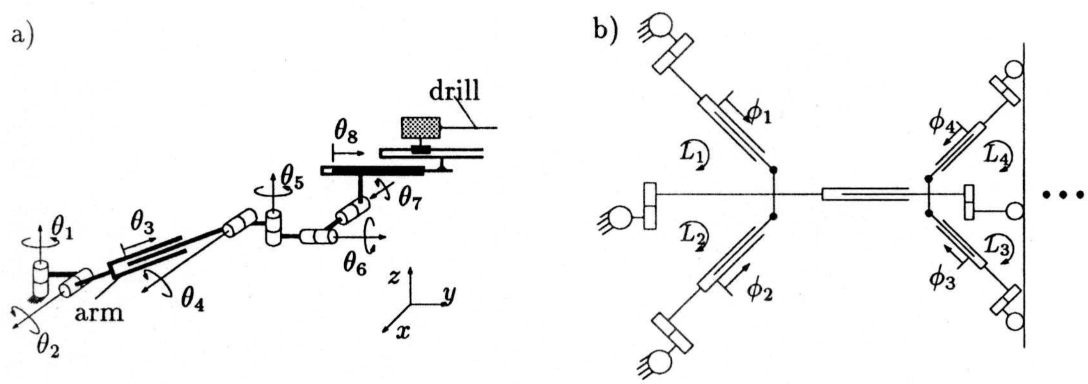

Figure 2: Kinematic structure of the drilling boom (a) and of the closed loops (b)

Applying the joint coordinate formulation (Nikravesh 1988) the translational velocity $\dot{\boldsymbol{r}}$ and angular velocity $\boldsymbol{\omega}$ of an arbitrary point P can be calculated as

$$\dot{\boldsymbol{r}}_p = \boldsymbol{J}_p^r(\boldsymbol{\theta})\,\dot{\boldsymbol{\theta}}, \tag{1}$$

$$\boldsymbol{\omega}_p = \boldsymbol{J}_p^o(\boldsymbol{\theta})\,\dot{\boldsymbol{\theta}}, \tag{2}$$

where $\boldsymbol{J}_p^r(\boldsymbol{\theta})$ and $\boldsymbol{J}_p^o(\boldsymbol{\theta})$ are (3×8) Jacobian matrices. On the other side there are closed loops $L_1, \ldots, L_4$ (Fig. 2) due to the transmission mechanisms.

All closed loops can be solved explicitly by using the method of the characteristic pair of joints (Woernle 1988). Thus, for a given set of joint velocities $\dot{\boldsymbol{\theta}}$ a corresponding set of actuator velocities $\dot{\boldsymbol{\phi}} = [\dot{\phi}_1, \ldots, \dot{\phi}_8]^T$ can be explicitly found as

$$\dot{\boldsymbol{\phi}} = G(\boldsymbol{\theta})\,\dot{\boldsymbol{\theta}}, \tag{3}$$

where $G(\boldsymbol{\theta})$ represents the (8×8) regular control matrix.

3 CARTESIAN CONTROL STRATEGY

The drill rig under investigation is equipped with two redundant drilling booms. A mechanical system is called kinematically redundant, if the number n of degrees of freedom of the mechanical system is greater than the number m of variables strictly needed for accomplishing a given motion task which is formulated in Cartesian coordinates. The difference $n - m$ characterizes the degree of redundancy. Typically six joints are necessary for positioning and orienting a body within a prescribed workspace. The drilling boom has 8 DOF hence there are 2 degrees of redundancy.

The aim is to develop a controller which enables the operator to move the tip of the drill through Cartesian space either manually or automatically. Thus the problem is to find an appropriate set of joint velocities for a given set of translational and angular velocities of the drill whereby the redundancy of the kinematic structure has to be taken into account. This problem is well known as the inverse kinematics problem on the velocity level and various approaches have been developed (see Nenchev (1989) for an overview). In order to ensure a real-time implementation which requires computationally efficient algorithms appropriate control strategies for manual and automatic control have been developed which will be described in the following.

3.1 MANUAL CONTROL

The easiest way to handle a drilling boom is to move the tip of the drill through Cartesian space by manual control. Therefore, the operator defines the direction of the velocity by using two joysticks each equipped with 3 DOF whereby one joystick will be used to set the translational velocity of the drill and the other one will be used to set the angular velocity. The translational velocity of the drill denoted by the subscript e can be found by using Eq. (2) as

$$\dot{\boldsymbol{r}}_e = \boldsymbol{J}_e^r(\boldsymbol{\theta})\,\dot{\boldsymbol{\theta}}, \tag{4}$$

where $\dot{\boldsymbol{r}}_e$ is the translational velocity of the drill and $\boldsymbol{J}_e^r(\boldsymbol{\theta})$ is the corresponding Jacobian matrix. The angular velocity of the drill can be derived in a similar way as

$$\boldsymbol{\omega}_e = \boldsymbol{J}_e^o(\boldsymbol{\theta})\,\dot{\boldsymbol{\theta}}, \tag{5}$$

with $\boldsymbol{\omega}_e$ denoting the angular velocity vector and $\boldsymbol{J}_e^o(\boldsymbol{\theta})$ is the corresponding Jacobian matrix. In the following Eq. (4) and Eq. (5) are written as

$$\dot{\boldsymbol{y}} = \boldsymbol{J}\,\dot{\boldsymbol{\theta}}, \tag{6}$$

where

$$\dot{\boldsymbol{y}} = [\dot{\boldsymbol{r}}_e^T, \boldsymbol{\omega}_e^T]^T \tag{7}$$

is a (6×1) vector and

$$\boldsymbol{J} = \begin{bmatrix} \boldsymbol{J}_e^r(\boldsymbol{\theta}) \\ \boldsymbol{J}_e^o(\boldsymbol{\theta}) \end{bmatrix} \tag{8}$$

is a (6×8) matrix. As soon as Eq. (6) can be solved for the unknown joint velocity vector $\dot{\boldsymbol{\theta}}$ the appropriate actuator velocities $\dot{\boldsymbol{\phi}}$ can be calculated with Eq. (3).

The crucial point now is to find a solution for the unknown joint velocities in Eq. (6) since the number of equations ($m = 6$) is smaller than the number of unknowns ($n = 8$). Thus Eq. (6) represents an under determined system of linear equations hence there is no unique solution rather than a solution space. For such kind of problems further criteria have to be formulated. A suitable criterion is to minimize the magnitude of the joint velocity vector $\dot{\boldsymbol{\theta}}$ whereby Eq. (6) has to be fulfilled. Such a criterion can be formulated with the *Lagrange*-multiplier method (Ben-Israel and Greville 1972) as

$$I(\dot{\boldsymbol{\theta}}) = \frac{1}{2}\dot{\boldsymbol{\theta}}^T Q\,\dot{\boldsymbol{\theta}} + \boldsymbol{\lambda}^T[\dot{\boldsymbol{y}} - \boldsymbol{J}\,\dot{\boldsymbol{\theta}}], \tag{9}$$

$$\dot{\boldsymbol{y}} = \boldsymbol{J}\,\dot{\boldsymbol{\theta}}, \tag{10}$$

where Q is a (8×8) symmetric positive definite matrix and $\boldsymbol{\lambda}$ is the (8×1) vector of *Lagrange*-multipliers. A general solution can be found as

$$\dot{\boldsymbol{\theta}} = \boldsymbol{J}^{\#}\,\dot{\boldsymbol{y}}, \tag{11}$$

with the generalized inverse

$$\boldsymbol{J}^{\#} = \boldsymbol{J}^T Q[\boldsymbol{J} Q \boldsymbol{J}^T]^{-1}. \tag{12}$$

For the special case that Q equals the identity matrix the generalized inverse $\boldsymbol{J}^{\#}$ corresponds to the *Moore-Penrose* inverse

$$\boldsymbol{J}^{\#} = \boldsymbol{J}^T[\boldsymbol{J}\boldsymbol{J}^T]^{-1}. \tag{13}$$

Since the computation of $\boldsymbol{J}^{\#}$ by Eq. (13) is very expensive a more efficient numerical evaluation such as the QR-factorization (Strang 1986) is applied. With the control scheme based on Eq. (11) the operator is able to move the drill in an arbitrary direction of the Cartesian workspace. A real-time implementation of this control scheme has been successfully tested on a redundant SCARA robot. (Risse et al. 1995)

3.2 AUTOMATIC CONTROL

In automatic mode the drill has to be moved to different positions under different orientations. Thus, the movement between two locations has to be described by a trajectory. Applying the control scheme according to Eq. (11) results in a deflection of position and orientation, which are created by the time discrete realization of a controller and by disturbances. In order to ensure proper trajectory following the control scheme (Eq. (13)) has to be expanded by the feedback of position and orientation error (Banerjee et al. 1996).

4 COLLISION AVOIDANCE

The bulky geometric structure and the high dexterity of the drilling boom makes it possible that the operator drives one boom into the other or into the basket. Furthermore, it can happen that the drill collides with itself. In order to prevent machine breakdowns and high repairing costs, a collision avoidance strategy has to be added to the Cartesian control concept. This can be done by assuming the most endangered parts are surrounded by virtual geometric primitives such as cylinders and cubes (Fig. 3). Since the geometric structure as well as all joint coordinates of boom and basket are known the position and orientation of all the elements can be calculated (Banerjee et

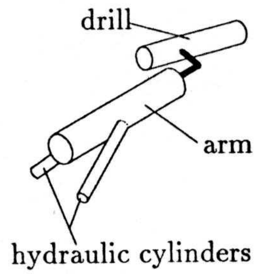

Figure 3: Geometric model of the drilling boom used for collision detection

al. 1996). The collision of two primitives is detected by solving simple linear equations. In case of an impending collision the control system stops the involved actuators automatically. This status will be kept as long as the operator doesn't move the system out of the endangered state.

5 MOTION CONTROL SYSTEM

Using the *Integrated Development Tools for Mechatronic Systems* (Anantharaman et al. 1995) the control system is programmed and tested on a workstation. The basic idea of this environment is that the control system can be developed using a simulation model of the drill rig. After completing the work the control software can be cross compiled for the real-time system without any changes. Therefore, libraries for real-time programming and device-handling with exactly the same programming interface have been developed for HP-workstations and real-time systems based on Motorola processors. The structure of the motion control system is illustrated in Fig. 4. The man-machine-interface allows

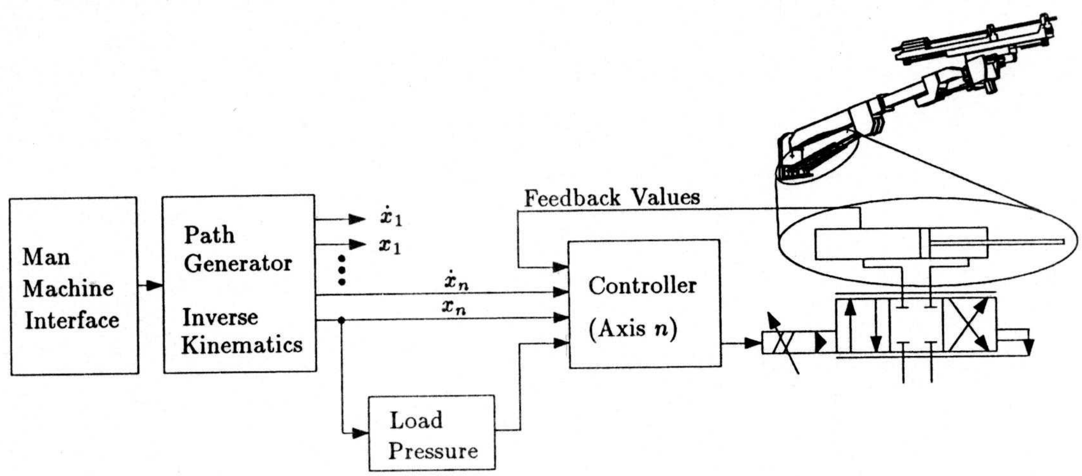

Figure 4: Structure of the motion control system

interaction with the operator and generates instructions for the PathGenerator. Using the manual mode, the PathGenerator calculates the desired joint velocities and positions for the decentralized non interacting controllers by using the inverse kinematic of the boomer model. Under automatic control smooth trajectories are determined for the motion between two Cartesian positions. For each axis the controller evaluates the input for the servo directional control valve using feedback values (position, pressure) from the hydraulic cylinder and reference values (position, velocity). The position of the piston is generated by a magnetostrictive measurement system as an absolute digital value. Additionally, the load pressure generated by gravitational forces is calculated and used in a feed-forward control strategy.

6 MAN-MACHINE-INTERFACE

Driven by the needs of aerospace and armaments industry innovative developments for man-machine-interfaces have been made for the improved interaction with complex technical processes. Since the mid 80's considerable advances in the subject of human-computer-interaction have been achieved by introducing graphical user-interfaces. Nowadays, the rapid development of extremely powerful and affordable computer hardware makes virtual reality applications possible. The need for interaction with the simulated reality leads to the upcoming of periphery such as data-gloves, head-mounted-displays or haptic-interfaces. In opposite, when observing the current state of man-machine-interfaces for heavy duty construction or mining machinery, it is quite obvious that the user interfaces are equipped with a fairly poor set of instrumentation (Fig. 5). This fact corresponds to the low degree of automation employed in today's heavy duty machinery.

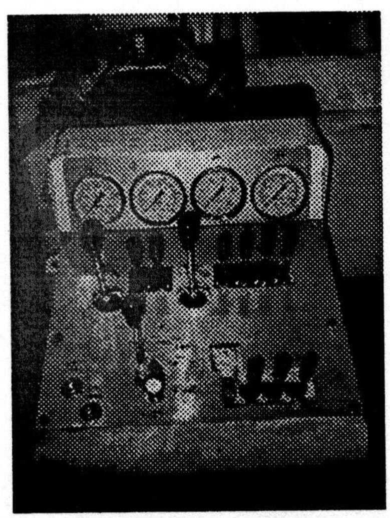

Figure 5: Conventional panel of a drill rig

With the objective to automate a drill rig to such an extent as it is proposed in this paper, it is inevitable to redesign the user-interface completely. Moreover, it must be kept in mind that the environment for the machine and its operator is extremely hazardous and that the personnel is usually not specially trained for handling automated machines.

In order to use the operator's superior abilities in pattern and signal recognition or global task planning, the approach of complementary allocation is chosen which takes in consideration that a human operator is flexible but not consistent in his behaviour however a machine acts vice versa (Schweitzer et al. 1995). Using this approach it is not the aim to replace the operator but to offer him a tool to make his tasks easier. Therefore, in this project the interaction concept of supervisory control (Johannsen 1993) is applied. The Cartesian positioning of the drilling booms for example will be – in the first place – accomplished by manual control, while the coordination of up to eight actuator movements is performed automatically by calculating the inverse kinematic equations described in section 3. The drilling process itself is controlled by the machine via the evaluation of status information such as drive speed, pressing force and feed speed of the drill. Meanwhile the operator is free to set up a new position for the second drill boom.

Fig. 5 shows the currently available user panel of the drill rig presented in Fig. 1. Eight hydraulic actuators can be accessed by directly manipulating the corresponding valve via a lever. Display of status information is very limited since just four hardware indicators are employed. A vital problem in designing a modern man-machine-interface for heavy duty machinery is the fact that there are only few in- and output devices available which are appropriate for an extremely rugged environment. Nearly the whole range of modern interaction devices to be associated with e.g. virtual reality is just suitable for laboratory usage, hence it is necessary to employ standard devices such as joysticks and LCD-monitors. The chosen approach of a new user panel for the drill rig is presented in Fig. 6.

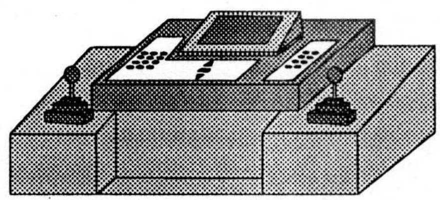

Figure 6: Concept of a graphically supported user interface

A general demand on a user interface should be the intuitive handling (Shneiderman 1993) of the implemented functions. Therefore, the user panel is split up into three functional sections. At first there are two joysticks for the input of position and orientation of the drilling booms. The second section contains push-buttons for the selection of standard actions such as "boring mill on/off" or "drill movement backward/forward" for enabling unexperienced operators to use the machine manually because all common standard functions are directly available. The third section provides access to the menus for automatic functions which can be programmed by presetting parameters. In addition to that the same menus display the state of various process variables, e.g. the actual depth of the bore-hole during the execution. It is a crucial point that the automatic functions are easy to handle. Therefore, the menus are presented as form-fillin dialogues (Shneiderman 1993) for convenient interaction between operator and machine. This approach is attractive because the full complement of information is visible, giving the user a feeling of being in control of the dialog. The following example is given to illustrate the use of the menus. There is one menu available to preset the drilling depth. It consists of four elements (state of the menu, actual drilling depth, desired drilling depth and a status bar). If the user selects the element containing the desired drilling depth, he can modify the input by incrementing or decrementing a default value. Selecting the state of the menu as "active" or "not active" respectively, means that during the next working cycle the automatic control of the drilling depth is activated or not. The actual depth of the bore-hole is displayed in the form of a numerical value as well as there is a representation of the degree of completion by the status bar.

This concept of a graphically supported user panel for a drill rig is actually to be realized as an important part of the Cartesian control system described above.

7 CONCLUSIONS

The Cartesian control concepts for complex machines requires sophisticated algorithms, powerful computers and appropriate man-machine-interfaces. Concerning these demands, an advanced control system for a drill rig equipped with two redundant drilling booms has been developed, which is just under realization. For this reason a full scaled test-bed for one drilling boom will be build up until the middle of this year to prove the described concepts of Cartesian control in manual and automatic mode, collision avoidance, feedback control and man-machine-interaction. If the results are satisfactory the control system will be implemented in a complete drill rig to obtain more experience under realistic conditions. The transfer of these concepts to machines for rock bolting is just under discussions.

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