Vision Supported Operation of a Concrete Spraying Robot for Tunneling Work

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Abstract

In tunneling and mining construction work, heavy and large manipulators are used to spray liquid concrete on the walls. These manipulators are usually operated manually with simple control units allowing to control all actuators independently.

In cooperation between industry and university, we have developed a novel automatic and human-oriented control system for such a manipulator. The new controller enables the operator to manipulate the tool in various modes, from purely manual actuation of single joints to vision-guided semi- and fully automated spraying of selected tunnel areas.

This paper presents the development and implementation of the control system designed for the concrete spraying robot Robojet®.

1 Introduction

The Robojet® sc-30 (figure 1) is a hydraulically actuated manipulator used in tunneling construction work. Its task consists of spraying liquid concrete on the walls of new tunnels using a jet as its tool. The design of this heavy and large manipulator with 8 degrees of freedom is ten years old, and the manipulator is being used worldwide. So far the manipulator has been operated manually with a simple control unit allowing to control the 8 actuators independently.

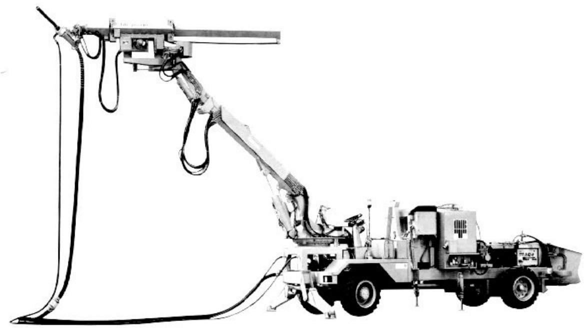

Fig 1. MEYCO Robojet sc-30

With this controller it is difficult to guide the jet along the wall of the tunnel while optimizing the spraying process and minimizing the losses of concrete. The operator must practice a long time in order to master the control in a satisfactory way.

The new human-oriented control system supports the operator in different ways. In one of the modes the operator can guide the jet directly in world-coordinates, using a space mouse, i.e. a 6 dof joystick. The calculation of the redundant inverse kinematics and the closed-loop control of the 8 hydraulic actuators is performed by the controller.

In an automatic mode it is possible to scan the profile of the tunnel in a selected area using a laser scanner and to subsequently automatically control the distance and orientation between the jet and the wall. The operator needs only to guide the tool center point along the directions of the tunnel wall with the space mouse. Furthermore, a fully automated spraying process based on vision data of the laser scanner within a selected area, which, however, is still under human authority, is being developed.

The aim of this control system is not to automate the whole task and to replace the human operator, but rather to simplify the task and enable the operator to use the robot as an intelligent and efficient tool [1, 2].

This idea of semi-automatic or user-supported control systems for manipulators has also been applied to other tasks, where interaction between the robot and the human operator is necessary, for example in the maintenance of electric power lines [3, 4].

The next section of this paper describes the structure and kinematics of the robot, and subsequently, a simulation tool with a 3D animated display is presented that allows to test the calculation of the manipulator motion, i.e. the inverse kinematic model and the generation of trajectories. The final sections describe the system and its components, in particular the laser scanner part, in detail.

2. Structure of the robot

The manipulator is mounted on a vehicle that is not moving during the spraying process. The location of the tool as well as the profile of the tunnel is therefore always described with reference to the vehicle.

Figure 2 shows the kinematic model of the Robojet with its redundant degrees of freedom.

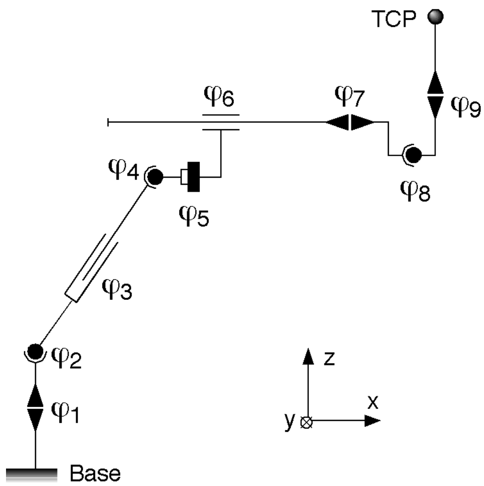

Fig 2. Kinematic model

All 9 joints are hydraulically actuated. Joint 9 is used for a small circling motion of the jet for a better distribution of the sprayed concrete. It has no effect on the calculation of the kinematic model.

The other 8 joints must be determined for a given pose of the jet, i.e. for the position of the tool center point and 2 angles for the orientation. As constraints for the redundant degrees of freedom, we used the following 3 static conditions for the variables:

- φ_3 = constant
- $\varphi_4 = f(\varphi_2)$
- $\varphi_5 = f(\varphi_1)$

The consumption of oil of the 3rd joint during large translational motions is too high to move it synchronously with the other joints. It remains therefore constant during the automated tasks and is only actuated manually.

Joint angles 4 and 5 are static functions of other joints. They are chosen so as to obtain a large workspace. For five given pose coordinates in the operational space and the three additional conditions, the angles of all eight joints are fully determined and can be calculated. Due to the complicated kinematic structure of the robot there is however no closed solution for the inverse kinematic model. The joint angles are thus calculated numerically with the Newton-Raphson method.

The maximum length of the manipulator is more than 10m, thus allowing to spray in tunnels with a diameter of up to 25m without moving the vehicle.

3. Simulation tool

MOBILE, a simulation and 3D graphic animation software [5] running on a SiliconGraphics workstation, is used to simulate the kinematics of the robot links and display its motions within a virtual tunnel (figure 3). The motions can be generated either by programming trajectories in a C++ program or online using a space mouse to guide the jet in world coordinates. This simulation is a very useful tool for design purposes and for investigating optimal poses and trajectories.

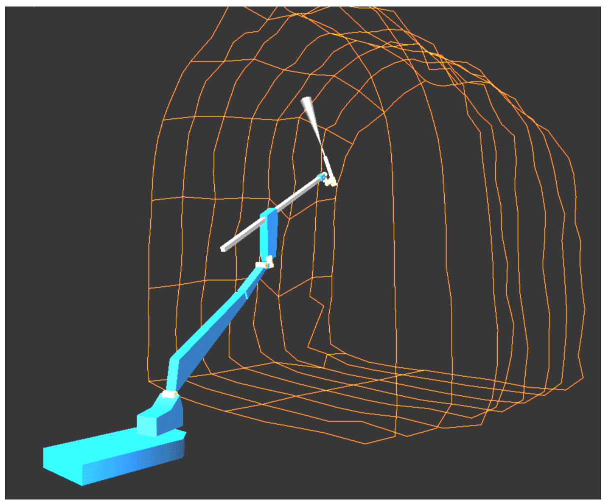

Fig 3. MOBILE simulation

This simulation tool is being extended now to create a virtual environment for training purposes. Including video sequences and profile data taken from real tunnels it will allow future operators to become familiar with the powerful control features of the manipulator in a safe way, before working with the real machine. The technique is similar to a training simulator for aircraft pilots and will considerably reduce the time and expenses for training.

4. Description of the system

In order to implement the new interface, the manipulator had to be equipped with encoders to measure the joint angles and with electrically controlled proportional valves for the hydraulic actuators. The sensors and actuators are connected to an Interbus-S peripheral bus system, that is controlled by a bus master board in a VME-bus system (see figure 4).

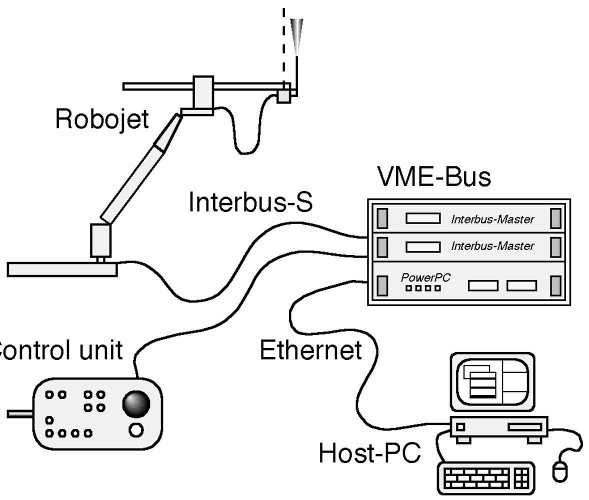

Fig 4. Hardware setup

Fig 5. Control unit

The robot is operated by a control unit (figure 5) that allows to select different operating modes, to switch on the concrete pump, to start the measuring process and other functions. The chosen functions are confirmed by lighting of the corresponding buttons. The digital signals from the control unit are transfered to and from the VME-bus system via a second Interbus-S connection. A space mouse [6] is integrated in the control unit and is connected to the processor board of the VME-bus system with a RS232 serial line.

The control software is running on a Motorola PowerPC 603 processor board and is programmed in the object-oriented real-time system D'nia/XOberon [7, 8]. A Host-PC allows the programming and monitoring of the system. It can further be used to change some process parameters that can't be controlled from the operator's control unit, such as the velocity of the jet during automatic spraying, the number of measurements in the scanning process and others. It is also used to visualize these parameters and to display a protocol of the complete operation cycle.

For operating the manipulator, the operator can choose the software from different modes as indicated in figure 6.

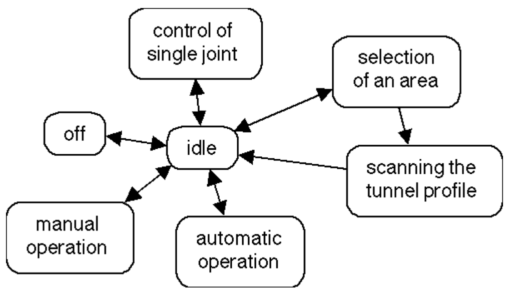

Fig 6. Operation modes

In the manual mode, the operator can guide the jet directly in world-coordinates, using the space mouse. Thus, the operator generates a trajectory in the cartesian space. By calculation of the inverse kinematics, the corresponding joint angles are determined. These values then serve as desired values for the closed-loop controller of the hydraulic actuators. This controller is a simple linear joint feedback position controller and implemented as a realtime process running on the PowerPC with a sampling period of 10ms.

5. Scanning and automatic operation

Automatic guidance of the tool along the tunnel wall requires a precise knowledge of the actual tunnel profile. This information is obtained with a laser sensor, that is mounted on the manipulator near the jet and inside a box that protects it during spraying processes. It is connected to the processor board with another RS232 serial line. The laser sensor IBEO PS100 (figure 7) is a time-of-flight device, able to measure distances from 1m up to 200m with an accuracy of 5mm. This laser sensor is also used for other distance-measuring applications in the tunneling industry [9].

The profile of a tunnel section of up to 300 degrees can be scanned by rotating joint 7 and thus the laser sensor about the tunnel axis. To start the measurement, the operator first needs to select an area to be scanned withing the robots workspace using a red marker laser that is integrated in the laser sensor. Scanning one profile of 300 degrees with 52 measurements then takes about 25 seconds.

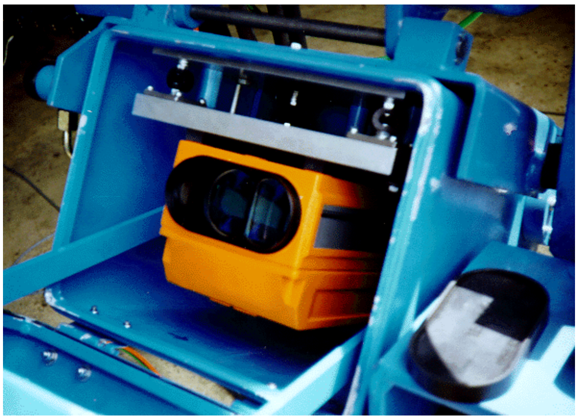

Fig 7. IBEO laser sensor

A much faster way to scan a profile would be to use a range-sensor, that is able to scan an area of 360 degrees in only one second. Such sensors have already been investigated for underground applications [10, 11], especially for scanning the tunnels horizontally for autonomous guidance of vehicles. Although the results with these sensors were quite promising, their robustness and long term reliability in a rough environment have not been proven so far.

Measuring the profile at different positions in the tunnel finally leads to a representation of the tunnel for the controller as seen in figure 8.

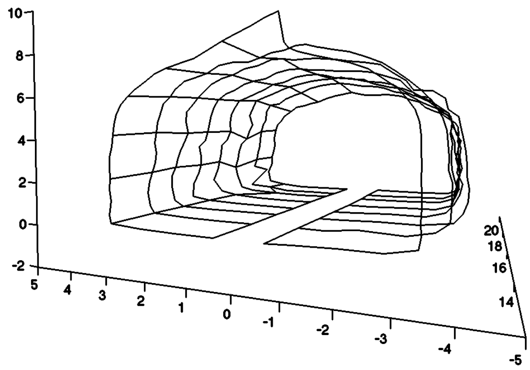

Fig 8. Scanned tunnel profile

This information on the tunnel profile is used to automatically control the distance between the jet and the wall and to keep the jet orientation within a certain angle with respect to the wall.

In a semi-automatic mode, then, the operator needs only to guide the tool center point along the directions of the tunnel wall with the space mouse.

Further automation is possible by letting the manipulator itself optimize the trajectories along the tunnel wall within the selected area. In this operation mode it is still possible, however, for the operator to intervene with the space mouse in order to correct the motion of the jet manually, for example, in dealing with obstacles, sharp corners or holes which require human experience for an optimal behaviour of the robot.

Fig 9. Robojet in operation

Another feature has also been made feasible by automatically creating information on the tunnel profile. When the profile is measured with the laser scanner before and after the spraying task, it is relatively simple to calculate the thickness of the concrete layer and the total amount of concrete used (figure 10).

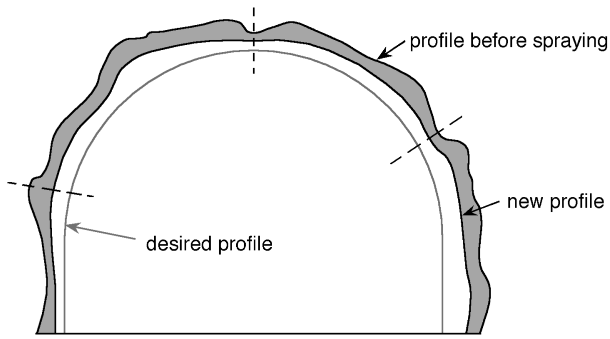

Fig 10. Profile measurement for quality control

This is a simple yet accurate method for quality control and enables to account for the actual use of concrete material. It is the integration of such additional features which finally makes this mechatronics approach so attractive to users.

6. Conclusions

The Robojet is a redundant heavy manipulator that used to be operated with simple manual control units by skilled personel.

In this paper, we presented a new semi-automatic control system that supports the operator in his work in different ways. The operator can concentrate his attention on the part of the work he regards as essential and which he himself chooses to do, i.e., the concrete spraying task, the planning and the supervising and he can delegate the less attractive parts, the heavy and repetitive work, to the machine.

A first version of this control system has been implemented on a manipulator and will be further tested in real tunnels. The tests allow us to improve the human interface, the closed-loop control of the actuators, the calculation of the optimal pose and the guiding of the jet relative to the tunnel wall. Furthermore we will make extensive use of the inherent information on the tunnel profile for quality assessment and for accounting for the actual concrete consumption.

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References

1. D. Diez, R. Roshardt, M. Hiller: Design of a man-machine interface for an interactive redundant heavy manipulator, Proc. 26. ISIR, Singapore, 1995, pp 93-98.

2. G. Schweitzer: Mechatronics for the Design of Human-Oriented Machines, IEEE Transactions on Mechatronics, vol. 1, no. 2, June 1996.

3. S. Tanaka, Y. Maruyama, K. Yano: Work Automation with the Hot-Line Work Robot System “Phase II”, Proc. IEEE ICRA, Minneapolis MN, 1996, pp 1261-1267.

4. M. Boyer: Systems Integration in Telerobotics: Case Study: Maintenance of Electric Power Lines, Proc. IEEE ICRA, Minneapolis MN, 1996, pp 1042-1047.

5. A. Kecskemethy: MOBILE - Users guide and reference manual, IMECH GmbH, Duisburg/Moers Germany, 1994.

6. Space Control GmbH, 82205 Gilching Germany, website: http://www.op.dlr.de/FF-DR-RS/SC/

7. D. Diez, S. Vestli: D’nia, an object-oriented real-time system, Real-Time Magazine, August 1995.

8. ETH Inst.of Robotics, 8092 Zurich Switzerland, website: http://www.ifr.mavt.ethz.ch/

9. IBEO Lasertechnik: Operators manual, Hamburg Germany, 1991.

10. G. Shaffer, A. Stentz: A Robotic System for Underground Coal Mining, Proc. IEEE ICRA, Nice France, 1992, pp 633-638.

11. S. Scheding, E. Nebot, M. Stevens, H. Durrant-Whyte: Experiments in Autonomous Underground Guidance, Proc. IEEE ICRA, Albuquerque NM, 1997, pp 1898-1903.