Mechatronics Design Concept and its Application to a Large Hydraulic Robot Manipulator for Concrete Spraying

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ABSTRACT

Mechatronics is an interdisciplinary way of combining the classical engineering disciplines for mechanical and electrical engineering and computer science. The objective is to build smart products and "intelligent" machines. Software is an integral part of such products and machines, and can be regarded as a machine element. The general concept of Mechatronics will be presented and a typical example of its application will be shown. A large, hydraulically actuated manipulator, being used in construction work for spraying ready mixed concrete on the walls of new tunnels and well known under the name of "Robojet", has been modified for easier control of its eight degrees of freedom and for performing parts of its tasks autonomously. The components of the system, the hydraulic actuators and the laser scanner for measuring the tunnel profile together with a novel automatic and human oriented control for the manipulator will be presented.

INTRODUCTION

Mechatronics has developed worldwide into a very attractive research area. It combines in a synergetic way the classical engineering disciplines mechanical and electrical engineering and computer science, leading to new kinds of products [1]. The term mechatronics for such a synthesis task came from Japan in about 1980, having been coined, it is said, by an employee of the Yasukawa Company. This interconnection of disciplines is actually not new: in aerospace engineering especially it has been well-known for a long time and has been successful. The actual development of mechatronics is based on the availability of relatively cheap computational power and it is further supported by the rise of versatile power electronics. The tendency is obviously to include much more information processing into the product to make better use of power and resources and to make it more versatile for the user. Subsequently, a definition of mechatronics will be given, together with a survey on the international activities in mechatronics in industry, research, and education. Some implications on relevant research directions such as design, production techniques, control, artificial intelligence, and man/machine interfaces will be discussed. As a typical example, the development of a classical machine - the Robojet® is a hydraulically actuated manipulator used in tunneling construction work for spraying liquid concrete on the walls of new tunnels - into a mechatronics product with new, technically and economically attractive features will be shown in more detail.

MECHATRONICS

Definitions

In recent years a number of different definitions for mechatronics have been suggested. At the ETH we have defined mechatronics in a way that clearly brings out the novel possibilities of combining different disciplines and the potential for machine intelligence:

> Mechatronics is an interdisciplinary area of engineering that combines mechanical and electrical engineering and computer science. A typical mechatronic system picks up signals from the environment, processes them to generate output signals, transforming them for example into forces, motions and actions.

It is the extension and the completion of mechanical systems with sensors and micro-computers which is the most important aspect. The fact that such a system picks up changes in its environment by sensors, and reacts to their signals using the appropriate information processing, makes it different from conventional machines (Fig. 1).

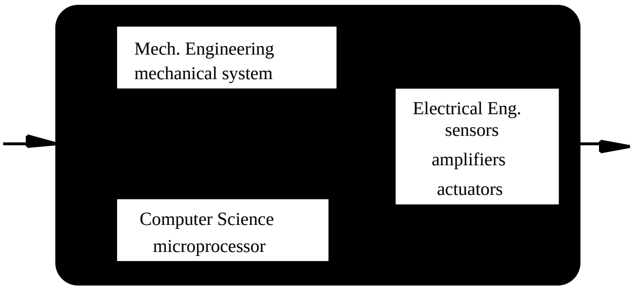

Fig. 1 - Mechatronic system, ETH definition

Examples of mechatronic systems are robots and controlled manipulators, digitally controlled combustion engines, machine tools with self-adaptive tools, contact-free magnetic bearings, automated guided vehicles, etc. Typical for such a product is the high amount of system knowledge and software that is necessary for its design. Furthermore, and this is most essential, software has become an integral part of the product itself, necessary for its function and operation. It is fully justified to say software has become an actual "machine element".

A more comprehensive definition of mechatronics has been formulated in England. It is represented by the graph of Fig. 2:

Mechatronics is the synergistic integration of mechanical engineering with electronics and intelligent computer control in the design and manufacture of products and processes.

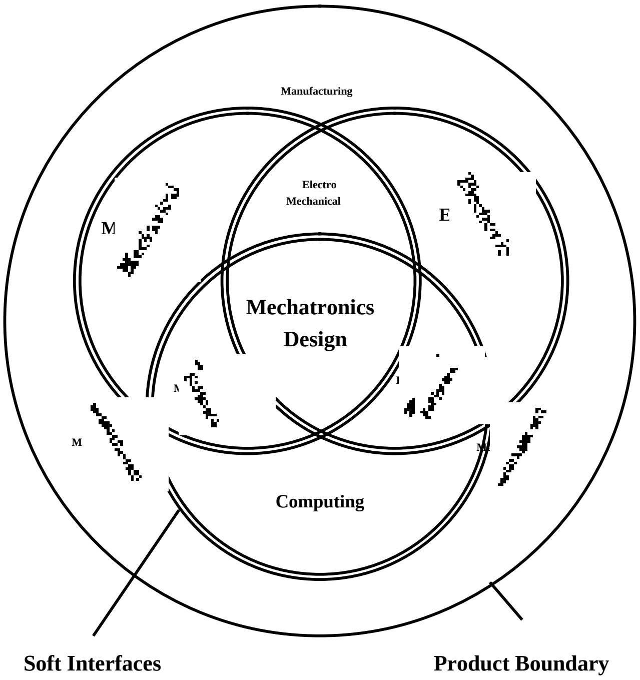

Fig. 2 - Mechatronic system, graphical representation according to [2]

In Japan the term Mechatronics is used rather pragmatically and with no hesitation. In the USA, until recently, the term itself did not seem to be really popular, and it was substituted by the somewhat lengthy expression "information-driven mechanical systems".

Mechatronics international

This section briefly describes the international activities in mechatronics as they are known to the author.

In Japan an International Conference on Advanced Mechatronics took place in Tokyo in 1989, organized by the Japanese Society of Mechanical Engineers (JSME) with International Societies cosponsoring the event, which for the first time gave a very good survey of this new field. Methods for industrially dealing with mechatronics are integrated into the Japanese industrial development of products. The universities, on the other hand, have only developed a few special curricula on mechatronics, much less than could be expected looking at the industrial success. These very successful product developments in Japan, be it cameras, video recorders, copy- or fax-machines, cars or robots, they have their roots in the satisfaction of technical innovations.

Further developments in mechatronics took mainly place in Europe where some countries have a high technology industry which is open-minded enough and well equipped for such synthesis tasks. Finland has initiated a very early sponsoring program for mechatronics which has been very well coordinated between industry and research institutes. In Germany, in November 1989, the VDI has organized a conference on "Kontrollierte Bewegungen - Mechatronik im Maschinen- und Fahrzeugbau", and there are numerous projects concerning mechatronics at individual universities, of states and of research supporting agencies. Especially in Germany and under cooperation of the European

Union, the term mechatronics has been extended to production techniques. Certainly the means for modern manufacturing, for example machine tools, robots, automated guided vehicles, can be seen as typical mechatronics products. In England the Institution of Mechanical Engineers (IMechE) set up an International Conference on "Mechatronics - Designing Intelligent Machinery" in Cambridge in September 1990. The initiatives of several university institutes are noteworthy, for example in Lancaster, Loughborough, or Dundee (Scotland). Mechatronics is now intensively sponsored by the Science and Engineering Research Council (SERC). In England a new journal has been published under the title Mechatronics, and one of the few textbooks [3] as well. In Holland, in 1992 a "Mechatronics-Platform" has been founded, with members from industry and university in order to promote the area in research and education. In Austria the University Linz has set up quite an ambitious curriculum in mechatronics and is supporting an informative homepage on mechatronics [4]. At the ETH Zurich, in 1984, a joint research group on mechatronics was set up. The members of the ETH Mechatronics Group come from the departments of mechanical and electrical engineering [5]. The group members cooperate in a synergistic way to support mechatronics in research and education, without giving up their obligations in their respective home departments.

In the USA recent activities appear also to favour the term mechatronics. In Brasil a few universities, for example USP, have begun to introduce mechatronics as a part of their curriculum.

Objectives of Mechatronics

Actual activities in mechatronics are concerned with generating motions in machinery in a controlled way. Controlling motions is necessary, for example, in industrial robots, electrical and hydraulic servo drives, or in magnetic bearings. The main topic is the application of classical methods of control techniques to mechanical plants. There are a number of conferences in this field, for example, [6]. In such cases, the contribution of mechatronics mainly consists of supplying and defining the demanding applications and integrating the control tasks into the technical system.

One could be led now to suppose that mechatronics has mainly the objective to improve technical properties, i.e., to make machines work faster and to make manufacturing cheaper. This assumption, however, appears to be too much one-sided, and covers the following much more important aspect with not enough scope. We are actually aware of the fact that technical appliances have become part of our daily life, and that we thus have to accept somehow a coexistence of technical systems with biological ones. This coexistence will certainly develop into a cooperation, and it will be this cooperation between biological or otherwise naturally unstructured systems and technical ones where mechatronics will play a very essential role. In such a cooperation it will be necessary to use machines which can be called intelligent and cooperative, in contrast to current industry where such an interaction is not yet usually needed. In industry, products and processes are designed from scratch, and therefore they are known, and dealing with them is a kind of straightforward action where the behaviour can be predicted, at least in principle. Even there, however, the complexity of tasks and situations is increasing, leading already to the use of unconventional tools like fuzzy control, neural networks, expert systems, and their combinations.

Therefore, for any such less structured environments we will need, in future, machines with some kind of intelligence. But it will nearly always be the case that this "machine intelligence" is not sufficient. It will most often be necessary to deal with exceptions, i.e. to overcome situations that could not be foreseen by the machine. The best exception handler we can think of is the human being. This brings us to the conclusion: We need machines which can work in an autonomous way up to a certain degree of complexity, and in critical situations or on a higher level of autonomy the necessary interactions with the human operator or user have to be facilitated and structured. Such man/machine interactions require an appropriate approach. In case of emergency, for example, it will not do for the machine, to be just equipped with a yellow warning light, a sounding horn, or a mere shutdown switch.

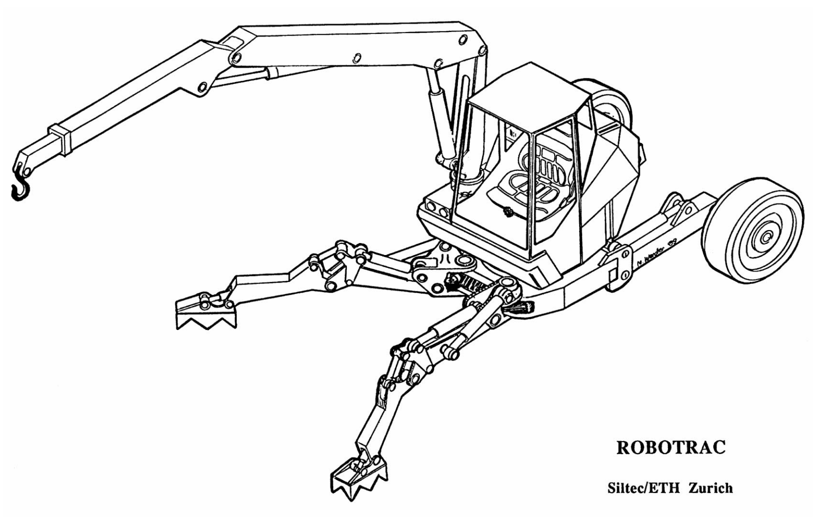

Fig. 3 - Robotrac®, a heavy load manipulator for rough terrain

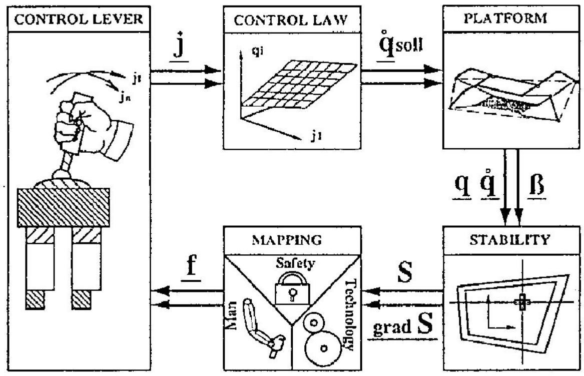

Fig. 4 - Signal flow of the stability feedback for preventing overturn, from [9]

We would like to be informed about the emergency situation, and about suggestions to get out of it. Working with such an intelligent tool, the operator can concentrate on his or her main task, and the machine will assist the operator by taking over the menial tasks and doing safety checks. This idea of semi-automatic or user-supported control systems for manipulators has also been applied to various tasks, where interaction between the robot and the human operator is necessary, for example in the maintenance of electric power lines [7,8]. Another example, the control of overturn stability for a mobile manipulator for rough terrain, the Robotrac® of Fig. 3, has been studied in [9], and the results can be applied to industrial applications such as a redundant heavy load manipulator [10], and the subsequently presented large concrete spraying manipulator for automated tunneling work.

The idea is the following: Path planning and manipulation of loads under complex working conditions has usually to be done by the human operator himself. Manipulating a heavy load manually however, e.g. with the help of a joystick, can jeopardize the static stability of the vehicle, as the operator can only judge the overturn stability in an intuitive and inaccurate way. According to his own uncertainty, the human operator behaves rather cautiously while controlling the platform. This impairs the efficiency of his work without providing safety for the system. The performance of such a man-machine system can be vastly improved by introducing electronic supervision and providing the operator with an appropriate feedback of some static stability measure. Thus the operator obtains support from the system while planning and performing the specific motions of the load. Critical situations can be foreseen and avoided. The signal flow for such a mode of operation is shown in Fig. 4: the manually actuated control lever is commanding, through an appropriate control law, the manipulator platform. The platform is described by a mechanical model from which a suitable stability measure and its gradient have been evaluated. This information is then mapped into reactional forces which act on the control lever, resulting in a modified force reflection.

New research challenges

These interactively cooperating, intelligent machines lead to new research topics in the control techniques of mechatronics and in other areas as well. It will be important that a machine and its components have learning capabilities, self-adaptation and self-calibration. Techniques such as the combination of neural networks, and fuzzy control with expert systems will further emphasize the importance of software. The complexity of the controlled mechanical structures and their environment, for example in mobile robots, will require hierarchical or behaviour-based control architectures. There will be redundancies in sensors and actuators, and as a consequence we will need qualified information processing for the data and command fusion. The safety techniques will have to be improved in order to master the interaction between man and machine. It is obvious that neighbouring areas such as work psychology, safety, and ergonomy will considerably increase in importance.

Another most important topic, especially for synthesis tasks such as in mechatronics, is the design of new products. The extension of the actual CAD design tools to incorporate mechatronic components and the art of using the potential of mechatronics to come up with smart products has yet to be developed. This deficit has been recognized and there are big efforts to support design education, in particular in the field of mechatronics.

As a remark it should be noted that there are certainly further engineering areas where the progressing use of information science will lead to new research areas strongly related to mechatronics. In material science, combustion engineering or bioengineering, for example, terms such as "smart materials", thermotronics or neuro-informatics indicate such directions.

New applications

Some new application areas can already be seen to develop in promising directions. One of them is the field of service robots. Even when the actual use of service robots is still very limited due to the still underdeveloped intelligence of these machines, there are already numerous research programs, especially on mobile robots, with prototypes for cleaning tasks in railway stations or schools, for use in construction or in agriculture and forestry, for distribution tasks in office buildings and hospitals, for working in hazardous environments, or for novel cars and transportation systems.

It is well-known that in aerospace many ideas of mechatronics have already been realized some time ago, and there, mechatronics has helped to make the large dimensions of space accessible to humans. And now, recently, the range of the very small is meeting growing technical interest, with mechatronics leading the way to micromaching and nanotechniques. These new fields will intensively use methods from mechatronics to make motions within the very small dimensions visible and controllable.

The medical area, too, mainly the support of diagnosis, surgery, and caretaking, where a controlled interaction between man and machine is indispensible, is going to be a prominent research and market area for mechatronic products.

Subsequently, a robot manipulator for construction work, with visual capabilities, as an example for a cooperative intelligent machine will be presented in more detail.

THE ROBOJET® MANIPULATOR

The Robojet® sc-30 (Fig. 5) 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. 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.

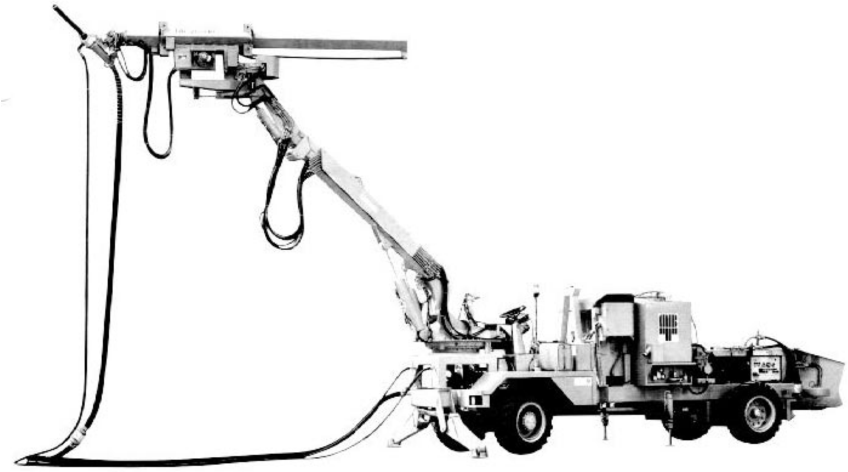

Fig. 5 - MEYCO Robojet sc-30, a large manipulator mechanism mounted to a heavy vehicle

In cooperation between industry and university, we have developed a novel automatic and human-oriented control system that 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 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 in 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.

The next section of this paper describes the structure and kinematics of the robot, and subsequently, a simulation tool 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 section describes the system and its components in detail.

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 refered to the vehicle. Figure 6 shows a kinematic model of the Robojet and table 1 technical data of some components of the hydraulic system.

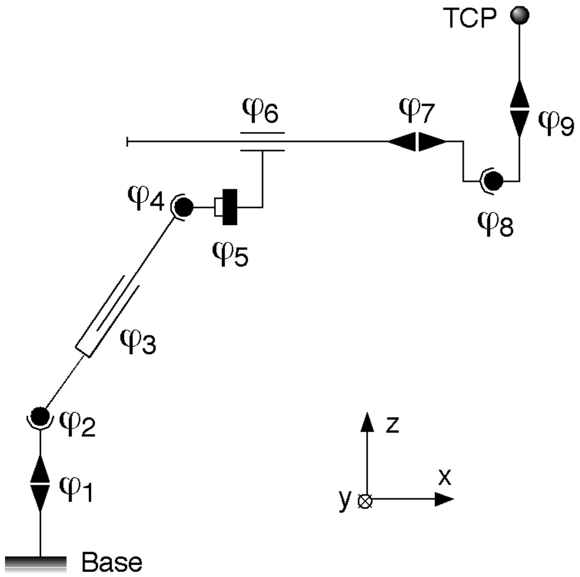

Fig. 6 - Kinematic model

pump-system	
pressure	**nom. 180 bar (max. 210 bar)**
max. oil-flow:	**56 l/min**
electric motor:	**15 kW, 1480 min^{-1}**
actuators	
joint 1:	**gerotormotor 173 cm^3 / turn (gear: i = 7.25)**
joint 2:	**hydraulic cylinder, D=150 / 55 mm**
joint 3:	**hydraulic cylinder, D=85 / 56 mm**
joint 4:	**hydraulic cylinder, D=100 / 40 mm**
joint 5:	**hydraulic cylinder, D=80 / 40 mm**
joint 6:	**gerotormotor 50 cm^3 / turn (gear: i = 3.55)**
joint 7:	**rotational motor 360**
joint 8:	**rotational motor 120**

Tab. 1 - Hydraulic system

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. To solve the redundancies, we used the following 3 static conditions for the variables:

- $\varphi 3$ = 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.

Simulation tool

MOBILE, a simulation and 3D graphic animation software [11] running on a SiliconGraphics workstation is used to simulate the kinematics of the robot links and display its motions within a virtual tunnel (Fig. 7). 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.

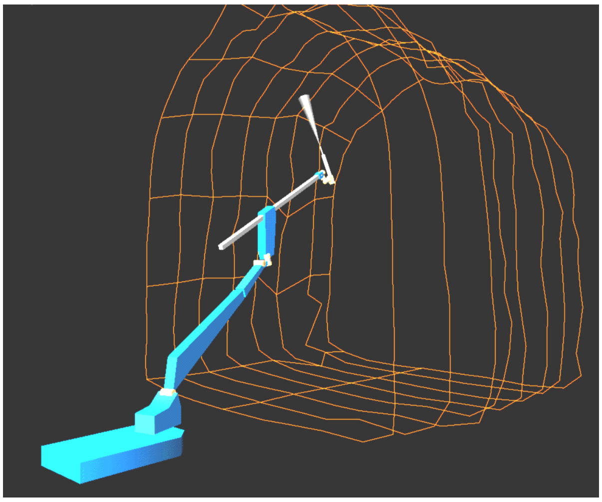

Fig. 7 - MOBILE simulation

This simulation tool is being extended now to create a virtual environment for training purposes. Making use of 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.

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 (Fig. 8).

The robot is operated by a control unit (Fig. 9) 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 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 [12]. 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 flow through 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.

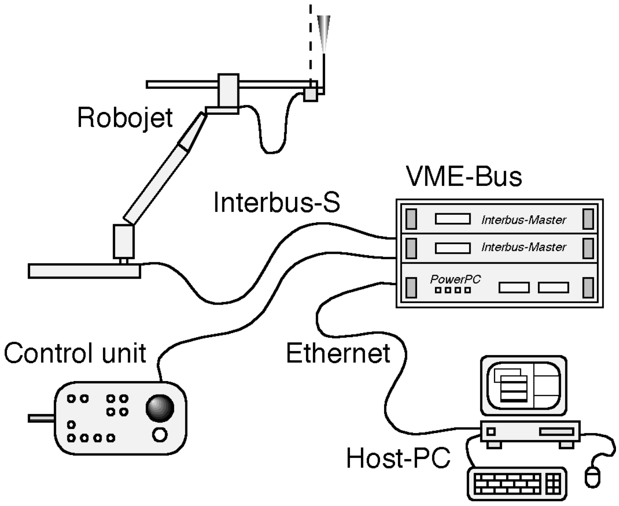

Fig. 8 - Hardware setup for the control system

Fig. 9 - Control unit

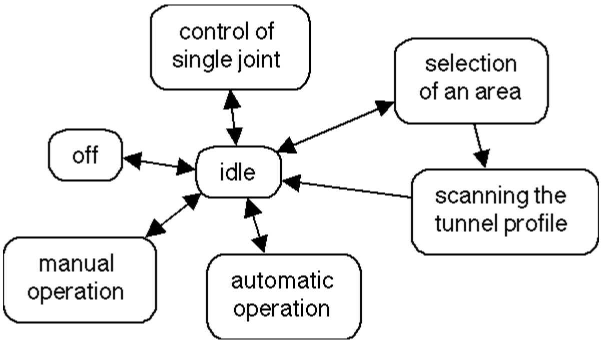

Fig. 10 - Operation modes

For operating the manipulator, the operator can choose the software from different modes as indicated in figure 10. In the manual mode, the operator can guide the jet directly in world-coordinates, using the space mouse. The operator generates thus 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 real-time process running on the PowerPC with a sampling period of 10ms.

The scanning of the tunnel profile is done in the following way: a laser scanner 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 (Fig. 11) 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 applications in the tunneling industry [13]. Further methods to scan profiles of tunnels and mines for underground automation applications are described in [14].

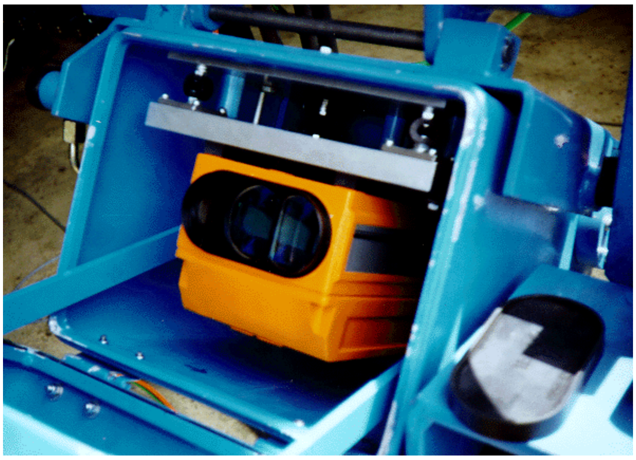

Fig. 11 - IBEO laser sensor

The operator first needs to select an area to be scanned within the robots workspace using a red marker laser that is integrated in the laser sensor. By rotating joint 7, a profile of up to 300 degrees can be scanned. Measuring the profile at different positions in the tunnel finally leads to a representation of the tunnel for the controller as seen in figure 12.

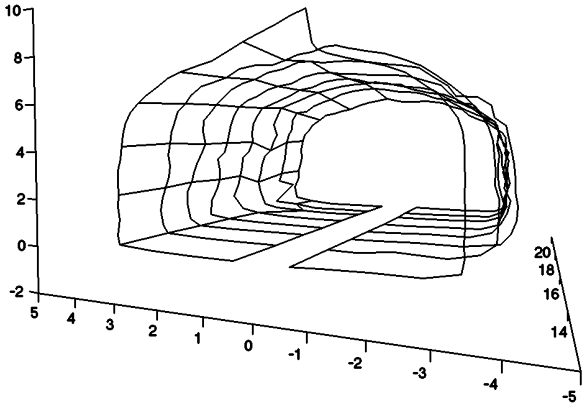

Fig. 12 - Scanned tunnel profile

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. 13 - 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. 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 the mechatronics approach so attractive to users.

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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