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CONTROL OF A LARGE HYDRAULIC MANIPULATOR FOR DECOMMISSIONING TASKS

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1. DESCRIPTION OF THE CARRIER SYSTEM

The carrier system is an existing, hydraulically actuated large range manipulator (EMIR). It consists of a base mounted on the ground or on a lorry, the arm package and the wrist. The base carries the arm package on a swivel axis. The arm package consists of five arms connected with rotational joints each of which is actuated by hydraulic cylinders whose translational motion is transformed into a rotation by means of linkages. The last arm carries the wrist with another three rotational joints driven by hydraulic motors. Both hydraulic motors and cylinders are actuated by solenoid controlled servo valves. The mechanical structure of the arms consists of light weight fine grain steel box profiles. This design yields a highly redundant (nine degree of freedom) manipulator with 22.5 m reach and 6000 N payload. The high degree of redundancy makes the manipulator very dexterous, e.g. it can work below its base or avoid obstacles in its workspace.

As a descendant of a concrete pouring mast, EMIR had as original control system a box with a set of joysticks directly controlling the hydraulic valves thus allowing only for single joint control. In a previous project /1,2/ KfK has developed a PC-based control system that allowed control of position or orientation of the tip of the mast by means of a single joystick. Due to elasticity of the mechanical structure, compliance in the hydraulic drives and safety elements in the hydraulic circuit the system is inherently unstable. An underlying oscillation damping control loop takes care of this characteristic by detecting and actively damping oscillations. On top of this control loop the manipulator control was built that allows joystick controlled motion of the boom with superimposed sensor input. The redundancy is resolved by pseudoinverse control with different optimisation criteria.

This unit was enhanced in the course of the decommissioning project as a carrier system for decommissioning tasks. The enhancement of this machine comprised the following areas:

- Adaption of a tool exchange system and extension of the hydraulic circuit
- Tasks specific sensor systems
- Enhancement of the manipulator control.

These three areas of enhancement were driven by the requirements of the decommissioning tasks and the requirements of automatic tool exchange. The first point will be covered in detail by another paper /3/.

2. TASK SPECIFIC SENSOR SYSTEMS

The machine in its original state as it became available for the project was equipped with 12 bit resolvers for angle measurements in the joints and pressure sensors to measure the hydraulic pressure in the cylinders. To accomodate the positioning and orientation accuracy requirements of the tool exchange system and of the tools in operation the instrumentation of the machine had to be considerably enhanced. Part of the instrumentation was mounted on the so-called A-plate. Fig. 1 shows the sensor arrangement on the A-plate. This plate was attached at the tip of the boom and carried the coupling units and the electrical and hydraulic connections. The mating plate called B-plate was attached to the tool.

2.1 Upgrade of swivel joint resolver

The azimuthal positioning accuracy depends heavily on the accuracy of the resolver of the swivel joint in the tower axis of EMIR. This accuracy is crucial for the docking process since the tool bench is set up in radial direction with respect to EMIR. To improve this parameter the resolver was equipped with a 16 Bit resolver electronic unit. This upgrade improved the positioning accuracy in azimuthal direction from about 30 mm to about 5 mm, measured on a radius of 15m from the EMIR base i.e. on the radius where the tool bench was positioned.

2.2 Inclinometer

In order to achieve utmost parallelism of A- and B-plate during the docking process a two axes inclinometer was installed on the A-plate. This installation was designed to measure horizontal inclination of the A-plate while approaching the B-plate of a tool resting horizontally in the tool bench.

2.3 Proximity sensors

The internal sensor systems of EMIR, the aforementioned resolvers do not allow for sufficient positioning accuracy on approach of the concrete surface. Hence the enhanced manipulator control relies on sensor information that provides the distance relative to the approached object and allows to calculate velocity information from these signals. The distance data are provided by four LASER proximity sensors mounted in the four corners of the A-Plate. These LASER sensors are high performance devices with a range of 100 - 2000 mm and an accuracy of 3 mm. They feature a built-in microcontroller that allows to configure several functions like interface parameters and sampling rate. The analog interface was used for communication with the EMIR control system. The sampling rate was set to 40 Hz.

During the approach of a concrete surface to be processed the proximity data provided by the four proximity sensors are evaluated to derive the orientation of the wrist relative to the concrete surface. For this task the inclinometer is of no help, since it measures inclination relative to the direction of gravity while the surface may in the general case be arbitrarily oriented in space. The orientation information derived from proximity data of the LASER sensors is then used to adjust the wrist such that the shroud of the microwave device or the suction pad of the core drill are parallel to the concrete surface. Then again the proximity information is used to slowly approach and to smoothly touch down the tool on the surface.

2.4 Force/torque sensor

A force/torque sensor developed in an earlier EMIR project was integrated with the tool exchange system. It has a range of 0 - 10 KN and 0 - 10 KNm and an accuracy of 50 N and 50 Nm.

The device is mounted at the very end of the arm hence it is crucial to save as much weight as possible. Due to an optimized design the selfweight is only about 500 N. The main purpose of the force torque sensor measures forces during docking and during processing of the concrete surface.

3. MANIPULATOR CONTROL

Precise motion with EMIR is difficult to achieve as it is far more compliant as typical industrial robots. The deflections in the arms are not measured by the joint angle resolvers. The control system tries to compensate the compliance by internally calculating the deflection in each configuration. This measure together with the 16 bit resolvers allowed for positioning accuracies of about 30 mm and orientation accuracies of about 1.5 °. Hence the development concentrated on three main points:

- Reduction of the accuracy requirements during docking by use of guides and compliant elements or by exploiting the compliance of the EMIR mast.
- Application of task specific sensor systems that supplied information relative to some external reference.
- Optimisation of the control system.

The first measure led to the application of these mechanical aids in the tool and toolbench design, while the second led to the selection of the inclinometer and the LASER proximity sensors and their integration in the control system.

The optimisation of the control system consisted in:

- Implementation of new motion modes:
  a) Gross motion mode for large motions with reduced requirements on positioning accuracy.
  b) Fine motion mode for precise positioning e.g. during docking or during work on a surface.
- Implementation of sensor data fusion:
  The objective was to fuse data of external sensor systems with the signals of the internal sensor systems depending on the application and signal quality.

Gross motion mode is based entirely on the internal sensor systems. Its main use is to move between toolbench and target or between targets. Sensitivity analyses showed that the first two joints as seen from the swivel axis are responsible for a large part of the positioning error. Hence for fine motion the first two arms are brought into a favourable configuration and then locked. The remaining three arms and the wrist now serve as a fine motion manipulator. This implies a significant restriction of the workspace.

The internal sensor system, the resolvers, is completely sufficient to determine arm configuration, position and orientation of the tool center point. Addition of external sensors such as inclinometer and LASER proximity sensors makes the instrumentation redundant. Now the control system decides dependent on the task which signals are used for the control. If high accuracy of position and/or orientation is required for some task the external sensor signals take precedence over signals calculated from the internal sensors.

This means in case of docking the position of the A-plate and its orientation about the local z-axis are calculated from the resolver signals while orientation about x- and y-axis are derived from the inclinometer signals.

In case of approach to a surface two position coordinates and the orientation about the z-axis are controlled based on resolver signals. The control of the remaining position coordinate and the orientation about the x- and y-axis relies on the signals of the LASER proximity sensors.
Figure 2 shows a schematic of the control system.

The combination of fine motion mode and task specific sensor based control yields the following results with respect to accuracy:

a) Docking: orientational accuracy better than 0.05 °

b) Approach to surface: Positional accuracy 5 mm (measured relative to the surface)
Orientational accuracy: 0.3 °

3.1 Possible enhancements of the control system

Even though all of the functionality required for the experiments was implemented in the control system, there would be ample space for improvements. The docking process consisted of several steps that were initiated individually from the control system operator or the operator of the control panel of the hydraulic system:

1. Move from base position in PTP mode to tool bench
2. Reconfigure boom to bring tool position into reach of the last three arms of EMIR.
3. Switch to fine motion mode (first two arms locked).
4. Switch on orientation control of the wrist based on inclinometer to adjust wrist orientation.
5. Turn on pilot valve for coupling system.
6. Turn on pressure release.
7. Extend coupling pistons.
8. Approach tool position in slow motion (1 cm/s) until force/torque sensor detects a contact force.
9. Move vertically until contact force has reached a limit of 1500 N.
10. Initiate coupling cylinders to drag A- and B-plate together.
11. Check signal of initiators to verify that A- and B-plate are coupled.
12. Turn off pressure release.
13. Move tool vertically upwards out of the tool bench.
14. Turn off orientation control.
15. Switch to gross motion mode.

16. Approach target.

Time constraints did not permit to cast these steps into an automatic procedure which would do the docking (and the undocking) automatically as soon as the operator has specifed the tool to pick up. Such an automatic procedure would relieve the operator from the tedious task of running all these steps in the proper sequence while continuously monitoring important quantities like forces, torques and pressures. Moreover safety trips could be built into the system that would e.g. stop the docking procedure when no pressure release has taken place.

Similar automatic modes could be implemented for path controlled approach to a target maintaining orientation of the wrist and for smooth touch down on a surface.

4. CONCLUSION

A large hydraulic manipulator has been enhanced as a carrier system for decommissioning tools. The enhancements included mechanical modifications, selection and adaption of sensor equipment and control system development. Experiments on a non contaminated test site have taken place in fall 1992. These experiments confirmed the viability of the concept. Work remains to be done in the area of radiation hardening of the components, automation of the tool exchange and automatic performance of decommissioning tasks.

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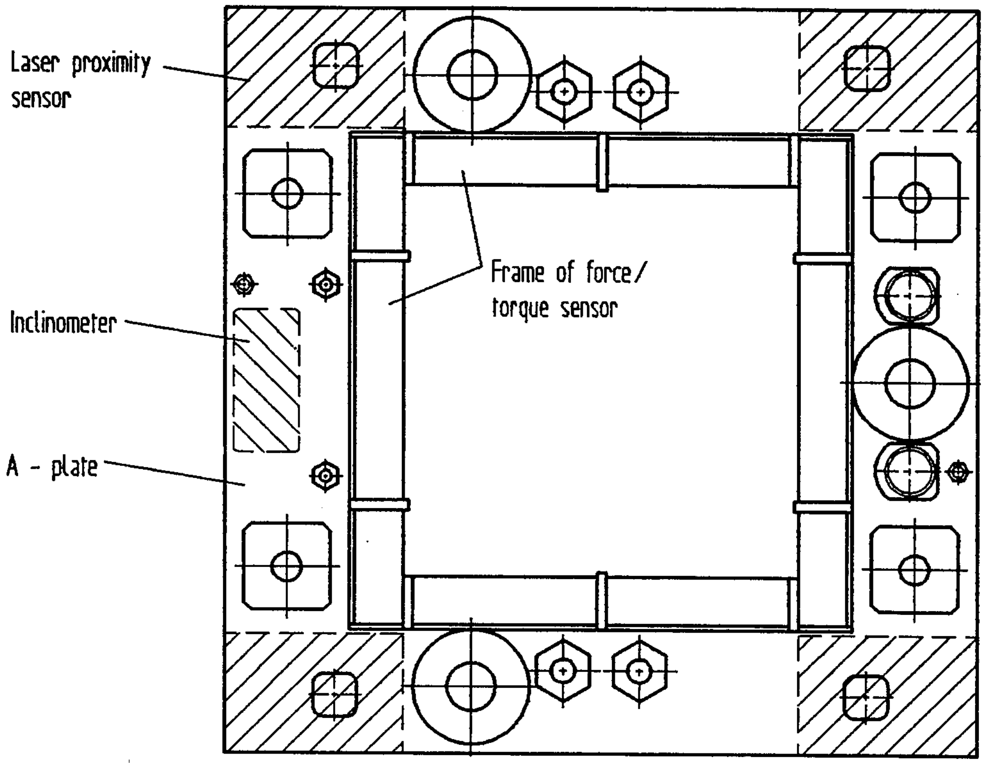

Figure 1: Sensor arangement on A-plate

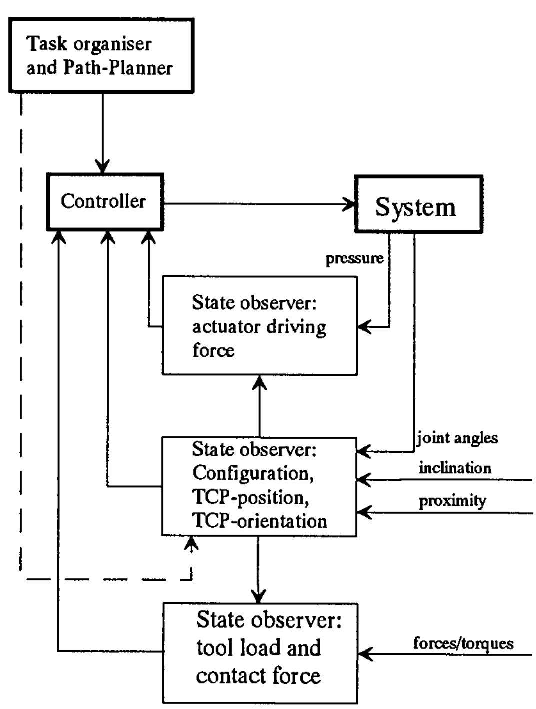

Figure 2: Schematic of control system