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A Multi-Layered Controller Approach for High Precision End-Effector Control of Hydraulic Underwater Manipulator Systems

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Abstract— **This paper presents a multi layered control architecture for hydraulic deep-sea manipulators. The proposed architecture is implemented on a Schilling Robotics Orion7P manipulator as example for a widely used deep-sea manipulator. In a number of experiments the improved precision of the new controller is shown. As application example for this improved precision the automated plugging of a deep-sea connector was evaluated and implemented.**

I. INTRODUCTION

ROV-based manipulators are one of the few possibilities to manipulate objects in the deep-sea environment. With increasing demand for facilities and structures in depths beyond the access of traditional divers and the increasing complexity of such structures, the challenges and applications for manipulator systems are steadily increasing. In order to match these requirements either new manipulation paradigms or novel control systems are imperative. This paper focuses on end-effector control of hydraulic manipulator systems. High precision manipulation is desirable, but poorly supported by industrially available deep-sea manipulators. We present a computer-based control approach which increases the effective precision of such systems by nearly an order of magnitude without any physical changes to the manipulation system. This allows a completely new range of tasks to be executed with certainties usually only attainable with industrial automation robots (which in turn are unsuitable for the underwater realm) or experimental, electric underwater manipulators (e.g. [1], [2]), which do not meet the speed, reliability and strength requirements of underwater intervention missions.

In the past many tasks (e.g. plugging) were only executable on a trial-error basis and the implicit use of the free-floating base-vehicle as elastic element. Underwater plugs only can cope with limited deviation during plugging (usually in the order of 1°, see figure 1), which can be extended by a factor of two if passive compliance devices (e.g. rubber fittings) are used. With a standard ROV manipulator, this precision simply cannot be reached, resulting in the 'stochastic' plugging described above. Here the ROV simply acts as additional elastic element preventing damage to both the connector and receptacle. Typical plugging rates with this type of setup are in the order of hours, and straining for material and operator.

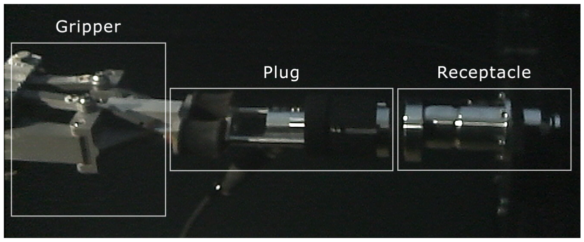

Fig. 1. Plugging restrictions for underwater connectors with the Gisma Series 80 as Example connector

II. PROBLEM ANALYSIS

Commercially available deep-sea manipulators are usually built for master-slave operation, which is widely used in ROV-manipulator systems. The design of control systems for such manipulators is focused on intuitive usability for the operators. Precision is no major design criterion, since due to master-slave operation the maximally reachable precision is limited by the operator, not the control system. This changes when manipulation systems start being computer controlled. In [3] a computer-based control for an Orion7P manipulator is described and further work (e.g. [4], [5]) shows the benefits of such approaches. Since the control strategy in [3] is based on the idea of emulating the master controller in order to control the manipulator, the precision restrictions of the original system are valid for the computer-controlled system as well. While higher precisions are physically possible with the hardware system, the control architecture does not allow higher precision.

A. *Control Scheme of the Orion7P Manipulator*

In order to break the problem further down, the Schilling Robotics Orion7P manipulator is considered as example for a widely used deep-sea manipulator. It has six joints plus a jaw, which is not covered in the following considerations. The six joints are actuated either by linear hydraulic cylinders (azimuth, shoulder, elbow, pitch) or rotary hydraulic actuators (roll and wrist). The linear travel of the hydraulic cylinders is

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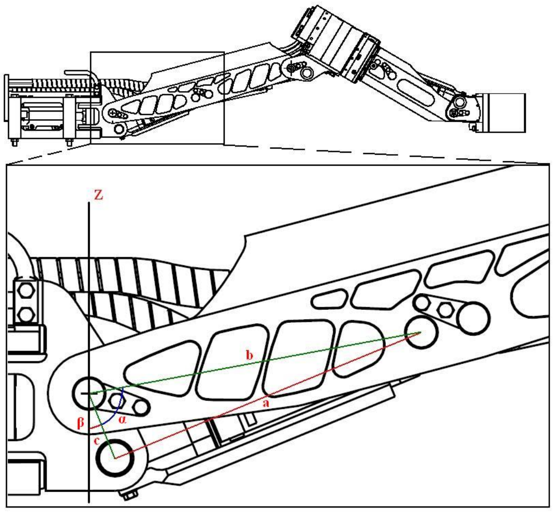

Fig. 2. Conversion of the linear hydraulic cylinder movement into joint rotation at the shoulder joint of the Orion7P. The cylinder travel a is converted into a rotation β.

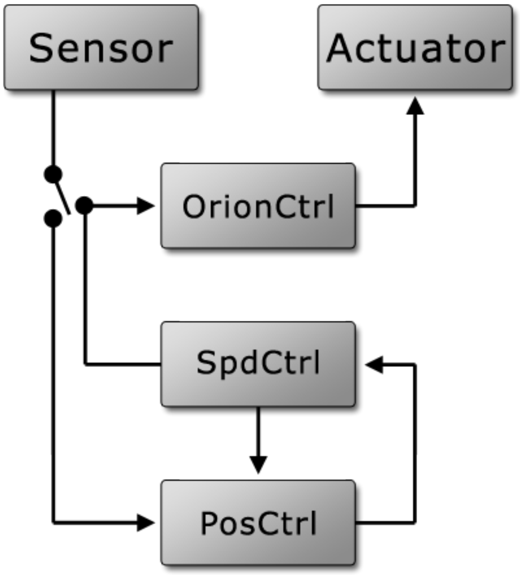

Fig. 3. Three-layer architecture for precise position control.

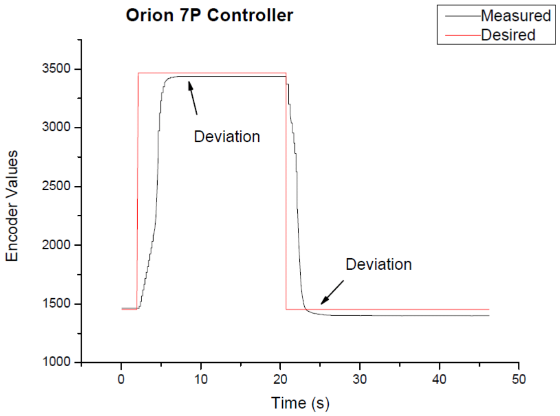

Fig. 4. The old joint controller. After reaching a steady state, the measured and desired positions show significant deviation.

converted to rotary joint movement as seen (exemplary for the shoulder joint) in figure 2. The flow of the hydraulic oil for all actuators is controlled by a series of electro-mechanical valves placed in the valve pack. At the same time, the acutator's positions are sensed by magnetic position encoders, yielding measurements of all actuator's current positions. For all further considerations the hydraulic oil is considered as an incompressible fluid, which is valid for the magnitudes of interest in this work. Further we do not consider the delay which is induced between valve and actuator due to the physical distance of both. This means, that the positions of all actuators are solely dependent on their initial position, the current and all prior valve positions:

$$a_t = a_0 + \int_0^t v_t dt$$

with a_t the actuator position at time t, a_0 the initial actuator position and v_t the valve position at time t. Using the notation from figure 2 and [3], the joint angle θ_t can be described as

$$\theta_t = \beta + \cos^{-1}\left(\frac{b^2+c^2-a_t^2}{2bc}\right)$$

which both combined yield the joint angle as function of the valve position v_t.

The Orion7P provides a microcontroller-based position controller for all joints, which regulates the valves in such way that the actuators reach a desired encoder position. This encoder position can be treated as direct measurement of the actuator's current position, and lies in the rage of $0 - 4096$. An ideal controller would always reach exactly the desired encoder position, without any overshoot or deviation. After analysis of the Orion7Ps controller, it became apparent that it utilizes a linear position controller for each joint. It shows considerable deviation in the magnitude of 130 encoder steps, with both overshoots and undershoots depending on the movement direction. These 3% encoder deviation would mean a maximum joint deviation of 3.6° in the azimuth joint if the actuator-joint relationship was linear, but considering the non-linear relationship this even rises to 4.2° of joint deviation in the worst case. For the other joints these values are in the same order of magnitude. A straightforward solution would be the replacement of the implemented controller with a better one. However the aim of this work was to improve the manipulator's accuracy without changing the hardware or respective the hardware-near software/firmware.

III. PROPOSED SOLUTION

The aim of the new architecture was to improve the joint position accuracy until the deviation is reduced to under 1°. The basic functionality of the original algorithm has to be retained, meaning that the new algorithm needs to implement a position controller as well. Since the Orion7P's position

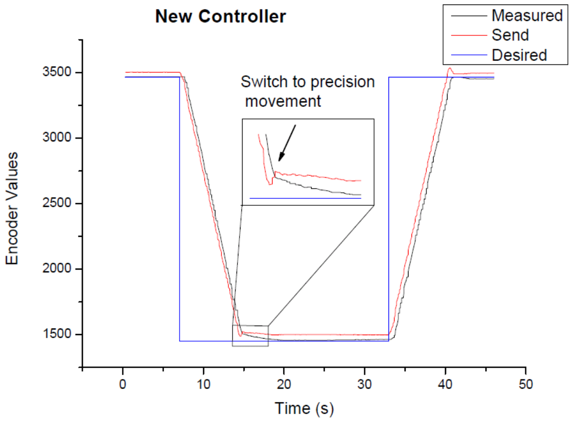

Fig. 5. The new joint controller. Instead of producing the overshoot, the controller switches to precision movement and greatly reduces deviation. At the same time overshoot is prevented.

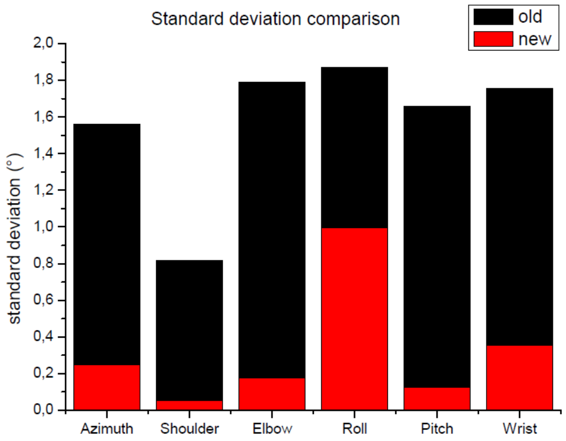

Fig. 6. Comparison of the standard deviations during position measurements between standard algorithm and the new, proposed algorithm.

controller cannot be circumvented, we were forced to base our control architecture on its low accuracy.

In order to increase precision we added two additional control layers: an adaptive speed control layer and a second position control layer. The second position control layer has the desired sub-degree precision. The idea is to use the adaptive speed controller in order to allow very slow, precise movements. Since the final aim is to reach specific positions, the second position controller manages this speed controller to achieve the desired high position precision. This setup is shown in figure 3. The speed controller uses a simple trick: Instead of giving one position to the Orion controller, it sends a new position at each controller iteration (running at the Orion controller frequency of 12.5Hz). Since the movements achieved this way are very small, the Orion controller does not apply any ramps to them, but tries to reach them directly. This results in the Orion controller staying shortly behind the speed controller, which gives a new position before the Orion controller reached the previous position (see also figure 5). By varying the size of the gap between the reached position and the sent position, the speed can be selected. In order to achieve position control, the second position control layer manages this adaptive speed controller. It selects the speed controller's speed in such way, that the resulting joint position converges to the desired joint position. To achieve this, it has to be aware of each joint's behavior, e.g. if it tends to overshoot or undershoot before reaching the desired position. For each individual joint it overshoot/undershoot direction was determined and saved for use in the controller.

Figures 4 and 5 show plots of a single joint movement (in this case the elbow was selected as testing joint). Using the old controller, the desired position (given in encoder values) is directly sent to the manipulator (red plot line). The controller reacts on the new desired position, moving the manipulator. An acceleration phase, steady movement phase and deceleration phase are clearly visible. Unfortunately in the upward direction the target encoder value is never reached, leaving a gap. In the downward direction the desired position is overshot but not corrected, leaving a similar gap, which is the origin of the observed position deviation. The new controller introduces a third plot line, the 'send' line. This is the value which is actually send to the Orion controller. The desired position remains in the plot just as reference value. The gap between measured and send values which was described above, is clearly visible. When the measured position closes to the desired position (as seen in the magnified portion of the plot), the position controller's knowledge about the Orion controller's behavior in the current direction is used to prevent overshoot or undershoot. The result is a steady state at the end of the movement with only a very small deviation between the measured and desired position. This deviation mainly results from changes in hydraulic oil temperature and the accompanying differences in actuator behavior at small movements. Another property of the proposed controller is that the resulting movements are very smooth, reducing the strain on the mechanical components.

A drawback of the proposed system is its manipulation speed, which can be rather slow in the very high precision modes. Since there is a natural trade-off between speed and precision, this was addressed by automatically controlling the precision: If fast movement is required, the system automatically reduces its precision, and vice versa. This way operating the manipulator feels very natural for human operators using the computer control.

A. *Experiments*

A number of experiments were conducted in the Underwater Robotics Testbed at the DFKI in Bremen. Using its Hardware-ROV-Simulator (described in [6]), precise measurements and extensive experiments in a realistic environment on the real hardware were possible. The first series of experiments included the manipulator moving to 100 randomly generated positions using the old and new position controllers. This was repeated a number of times in order to reduce process noise. The combined sensor measurements are shown in figures 7

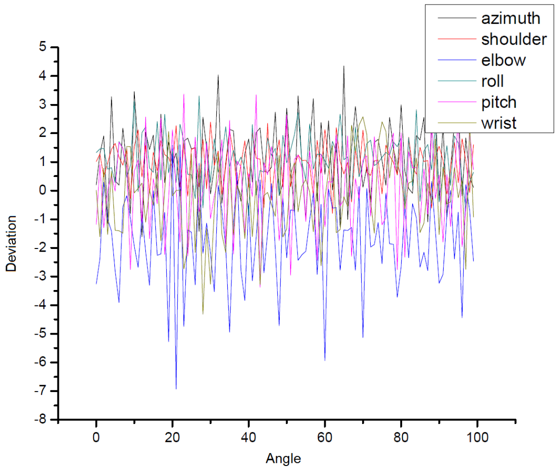

Fig. 7. Deviation between actual and desired position for 100 random positions of all joints with the old algorithm.

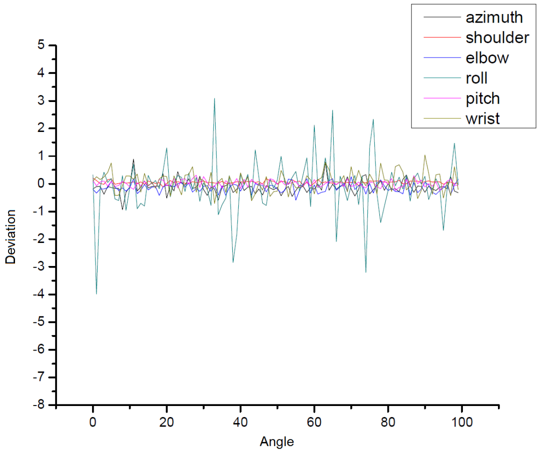

Fig. 8. Deviation between actual and desired position for 100 random positions of all joints with the new algorithm.

and 8. It can clearly be seen, that the angle deviation is lower when the new controller is used. However, the ’roll’-joint shows a number of steep deviation measurements. After careful evaluation it became apparent that, due to high inner-actuator-drag in the joint, a relatively strong force is needed to overcome initial friction. Since this friction term is non-linear, the linear controllers are not able to react reasonably. This stick-slip problem can only be overcome by the use of a non-linear controller, which was not finished in time for inclusion in this work. Figure 6 shows a summary of the standard deviations of all joints accumulated over all trials, with the numerical values for mean and standard deviation shown in table I. It is clearly visible, that the goal of mean deviation of smaller than one degree has been achieved for all joints. Only the ’roll’-joints shows a negative impact of the proposed controller, which was explained above.

The second experiment included successful completion of the benchmark, plugging of a Gisma Series 80 connector. This connector was designed to be pluggable with deep sea

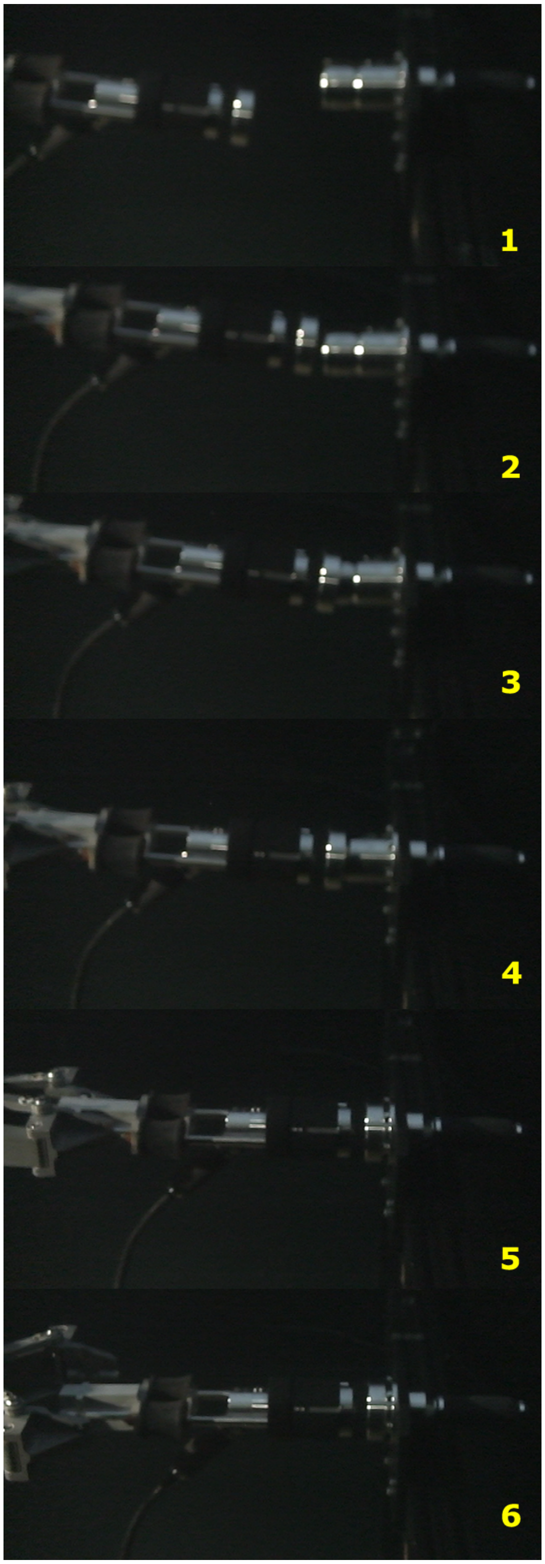

Fig. 9. Sequence of automated underwater plugging. 1) Plug approaches receptacle 2) plug aligned with receptacle 3) contact between receptacle and plug 4) linear movement for plugging initiated 5) passive locking mechanism engaged 6) plugging sequence finished.

TABLE I

JOINT ERROR MEAN AND STANDARD DEVIATION OF RANDOM POSITION EXPERIMENT

Joint	Standard Deviation	Mean
azimuth_old	1,13493	1,31544
shoulder_old	0,98187	0,76466
elbow_old	-1,75624	1,61274
roll_old	1,13942	0,87554
pitch_old	0,17006	1,53641
wrist_old	-0,1785	1,40309
azimuth_new	-0,11751	0,24714
shoulder_new	0,05457	0,05305
elbow_new	-0,13572	0,17667
roll_new	-0,07006	0,99482
pitch_new	0,00991	0,12278
wrist_new	0,07368	0,35274

manipulators such as the Orion7P. In order to plug it in a controlled manner, the manipulator's end-effector with the plug has to be positioned in front of the receptacle with a cartesian accuracy of at least 1mm, and a rotary accuracy of 1 °. Additionally, in order to then complete the plugging process, a linear movement of 100mm has to be executed. The testing setup is shown in figure 1. It consists of the claw of the Orion7P manipulator holding the plug, and the fixed receptacle. In order to prevent damage to the rigid setup, the plug's handle was de-coupled from the plug with two rubber connectors, making it passively compliant in case of strong stress. The plugging procedure consists of three phases: first, the manipulator moves the plug within one centimeter of the receptacle. Then the plug is precisely aligned with the receptacle until the top of both touch. The last step requires a linear movement in direction of the plug. Since the passive compliance handle made the plug tilt slightly down (due to its own weight), this linear movement had to be executed in two combined cartesian axes. A successful plugging sequence is shown in figure 9. The complete plugging sequence requires less than 80 seconds. Due to the problems with the 'roll'-joint as described above, the plugging was successful only in 50% of all trials.

IV. CONCLUSION

A multi-layered controller for position-controlled underwater manipulators was developed. Using the Schilling Robotics Orion7P as example, the feasibility of this approach and its increased precision could be shown in thorough experiments with the real manipulator. Without modification of the manipulator's hardware, the algorithm achieves remarkable performance and allowed completion of the benchmark of automated plugging of a deep-sea connector. The Gisma Series 80 connector was used for this benchmark, and could be automatically plugged in 50% of the trials. It is expected, that this ratio can be increased towards 100% after incorporation of non-linear controllers for the two rotary actuators, whose accuracy could not be improved by the presented algorithm due to strong non-linearities. The results were used to implement further automated tasks with the Orion7P, among them automatic position keeping as presented in [4]. It is expected, that a number of new applications using this technique will surface in the near future.

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