# C-Manipulator: An Autonomous Dual Manipulator Project for Underwater Inspection and Maintenance

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# C-MANIPULATOR: AN AUTONOMOUS DUAL MANIPULATOR PROJECT FOR UNDERWATER INSPECTION AND MAINTENANCE

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## ABSTRACT

*We present the new project C-Manipulator (funded by the German Ministry of Economics (BMWI), Grant No. 03SX231). The goal of C-Manipulator is the development of an autonomous, modular, dual manipulator system for underwater applications. This paper provides an overview over the project. It explains shortly the relevance of autonomous underwater manipulation. Then it describes briefly the state-of-the-art, explains the new vision-based control approach featuring visual servoing techniques and the planned manipulator system design featuring the Sub-C Network. Furthermore, a new developed indoor test-bed using a gantry crane for UUV-simulation is introduced, which will be used to test the manipulator system under realistic conditions and to prepare the system for a final test in the Baltic sea, which is planned for 2009.*

## INTRODUCTION

A increasing trend in the offshore industry is to mine deep sea resources, e.g. oil or mangan. At the moment this is a very expensive endeavor. Especially, cost-efficient 24h systems for the inspection and maintenance of deep sea production facilities are needed.

In the last decades more and more ROV (Remotely Operated Vehicles) with tele-operated manipulators have been deployed. Because of their permanent connection to the surface, they are inherently cost-intensive. Furthermore, highly trained personnel is necessary for the control and monitoring of these vehicles, which is mostly done from special ships. Thus, the running costs for installation and maintenance of underwater facilities are very high. By using an autonomous manipulator system, these costs can be significantly reduced.

One option is to use an autonomous manipulator on a ROV allowing to operate in situations too difficult to handle for manual control, which can be

1. Situations with poor visibility
2. Situations with communication fallout
3. Situations, where the hydrodynamic effects between the carrier system and the manipulator are leading to highly nonlinear control problems, which are very difficult for human operators.
4. Situations, where no highly trained personnel is available (auto-pilot)

A second option is to use the manipulator on an AUV (autonomous underwater vehicle), to enhance these systems for full autonomous inspection and maintenance and allow the conduction of manipulation tasks in areas where ROVs cannot go, e.g. under the artic ice.

Both options are relevant for the future of underwater robotics, the first option in the short-term and the second option in the long-term.

Therefore we set up the new project C-Manipulator (funded by the German Ministry of Economics (BMWI), Grant No. 03SX231). It is a 3-year project, which started in September 2006. The goal of C-Manipulator is the development of an autonomous, modular, dual manipulator system for underwater applications. We plan to design the system in a way that it can be adapted to different existing and future underwater vehicles, ROVs as well as AUVs.

The C-Manipulator will have the ability to detect, grasp, and depose predefined objects in its workspace and furthermore to connect certain objects (e.g. an underwater plug). Specifically, the system will be able to grasp objects up to 30kg (in air) which have a cylindrical shape or are attached to a special designed handle.

## STATE OF THE ART

Today most manipulators for underwater application are remotely driven in a master-slave-configuration. This means, that a manipulator pilot controls the slave-arm by moving a smaller copy of it, the master arm. The angle values of the master arm are periodically sensed and send to the control of the slave arm. Some very new and highly expensive manipulator systems include force-feedback into the master-arm but most arms are driven only by tele-observation via one or more camera-systems on the ROV.

First approaches to use manipulators on AUVs are already existing [1], but are still teleoperated, e.g. in the ALIVE project [2] a tele-manipulated arm is used to support the docking of an AUV.

Fully autonomous underwater manipulators prove to be very difficult although autonomous manipulation has already been achieved for non-underwater applications. In the underwater environment we are facing extra scientific and technological problems, which are among others:

1. hydrodynamic effects between carrier system and manipulator
2. dynamically changing visibility (e.g. maritime snow)
3. short range visibility (no natural light, only artificial light sources)
4. lack of force sensors in most of the underwater manipulators

The dynamic effects between carrier system and manipulator have been already studied by various scientists. These effects are important because the motions of an underwater manipulator can affect the attitude and position of the ROV which should remain stationary during manipulator operation. To compensate for the dynamic effect of the underwater manipulator on the ROV, force-torque information between the manipulator and the vehicle is used to regulate the states of the ROV [3].

If a force-torque sensor is unavailable (which is common for underwater manipulators), Ryu [1] proposes a disturbance observer to fill the role of the force-torque sensor. A disturbance observer estimated the interaction forces between the ROV and the manipulator based on an internal dynamical model of the system and feeds correction signals to the motion controllers.

Regarding the problem of localization Smith et. al. [4] showed that with high effort it is possible by usage of a laser scanner to localize a given object under water in the coordinate system of a stationary manipulator basis and to move the end-effector in the proximity of the object. Unfortunately the accuracy of this approach was not high enough for safe grasping and furthermore they faced the problem that the manipulator itself could occlude the object in the laser scanner view. To solve the complex inverse kinematical problem for generating the manipulator trajectory transputer boards have been used.

Summarizing, we can state, that all major problems of autonomous underwater manipulation can be solved, but till now no fully autonomous manipulator operating from a moving underwater carrier platform has been developed, because of the high number of problems. In the following we present, how we plan to achieve this goal.

## APPROACH FOR OBJECT DETECTION AND GRASPING

To avoid the problems of object occludence and of low precision in the object position estimation we are using the following approach.

The problem of grasping a object is divided into 3 steps:

1. object recognition in a scene
2. approaching the object with the end-effector
3. grasping the object

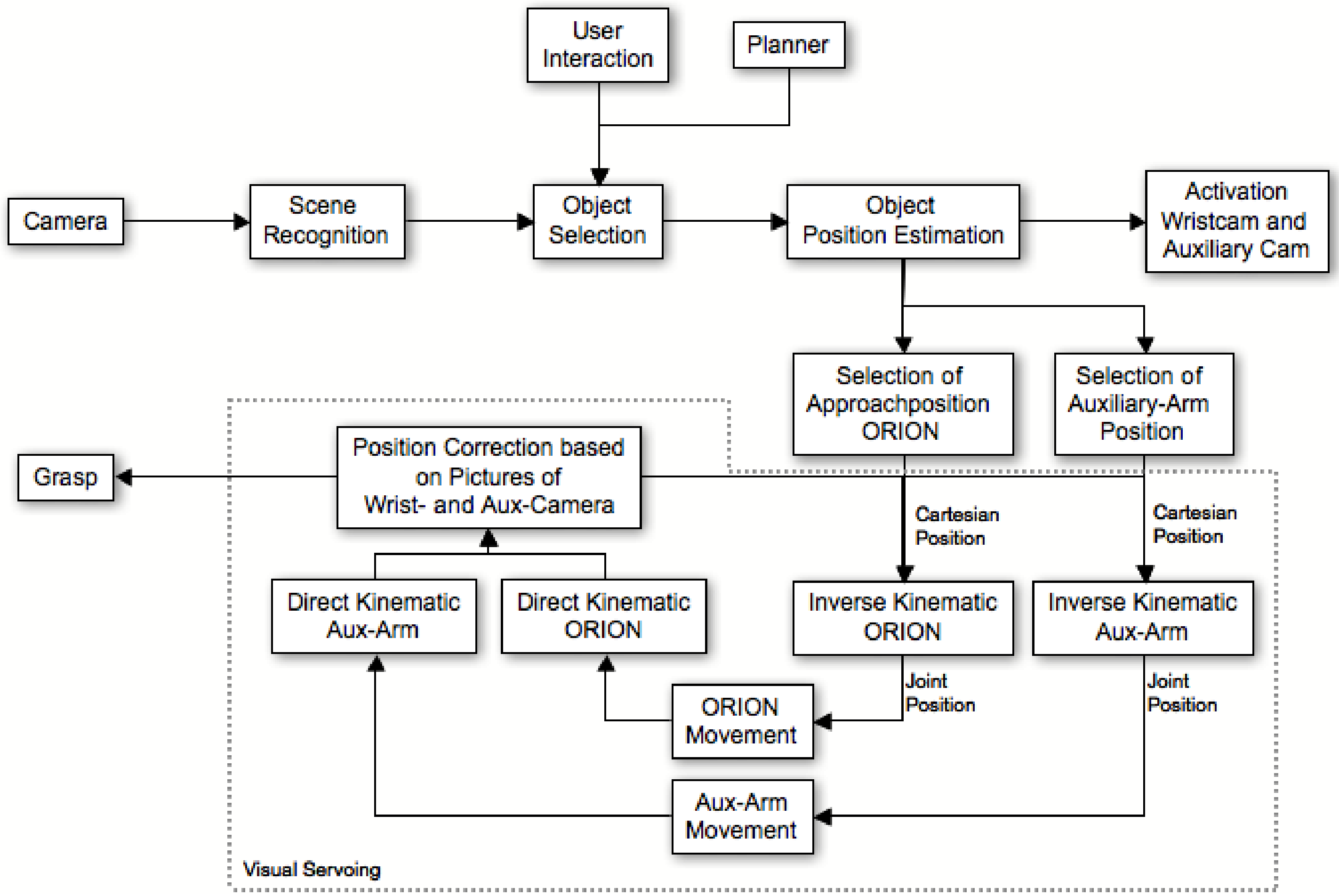


Figure 1. Control Approach Scheme

For scene analysis/recognition the usage of stereo camera systems is common in computer science. Stereo camera algorithms allow, if the relative distance and orientation between the cameras and their position in a fixed world frame coordinate system is known, to compute via correlation of the two acquired pictures the position and the size of an object in the observed scene. In principle, the same can be achieved with two pictures from a single camera, which is moved with a known motion vector.

The quality of the computation depends heavily on exact calibration of the camera system and on very low disturbances of the picture, e.g. due to dynamic effects like objects (e.g. small particles) moving through the scene.

Therefore, approaches based only on stereo vision can only be used for the control of manipulators if the environmental conditions are perfect, e.g. under lab conditions. In a real world environment, the computed data can be interpreted as a rough estimation of the real position, which is exactly the purpose of the stereo vision system in our approach.

The gained estimation of the position of the object is used for the first steps of reaching the object. The claw of the manipulator is moved to one of several pre-programmed approach positions. As soon as it has reached this position the system switches into the grasp mode. During the process of reaching, a second module is activated, which tracks via a wrist cam the object in question and fine-tunes the control of the arm in order to keep the end-effector aligned with the object to grasp. Thus we are using an additional visual servoing approach for improving the approach of the arm. While the end-effector nears the object, the visual quality of the wrist camera picture improves due to the decreasing distance, which supports the alignment behavior of the visual servoing module.

We believe that scene analysis together with visual servoing will prove to provide us with the necessary exactness to grasp objects and to allow plugging applications (e.g. to connect power cables).

In addition, this approach allows us to use simple correla-

Figure 2. The ORION 7P Manipulator ((c) Schilling Robotics)

tion approaches for object detection, which can be computed in real time. We only have to ensure that the first estimation of the position of the object is accurate enough to ensure that, when the end-effector moves into its direction, the wrist cam sees the object to grasp.

Figure 1 shows a graphical representation of the described control approach. The loop is closed inside the visual servoing part, which is emphasised by the dashed lines in the lower half of the figure.

## DESIGN OF THE DUAL MANIPULATOR SYSTEM

The system consists of a seven degrees of freedom (DoF) hydraulic manipulator as the main manipulation tool and a five DoF electric manipulator to move lights and additional cameras. The complete system is independent from the carrier vehicle and brings its own computation system and hydraulic aggregate. The chosen hydraulic system is the ORION 7P from Schilling (see fig. 2), which is normally used as a position feedback manipulator for master-slave control. It has 6 axes and a claw gripper.

In principle, we are exchanging the commands coming from the master arm with the command form our software control module. The arm will be equipped with a wrist cam on the hydraulic manipulator, which will be used for visual servoing applications. In addition, we will develop a stereo camera system

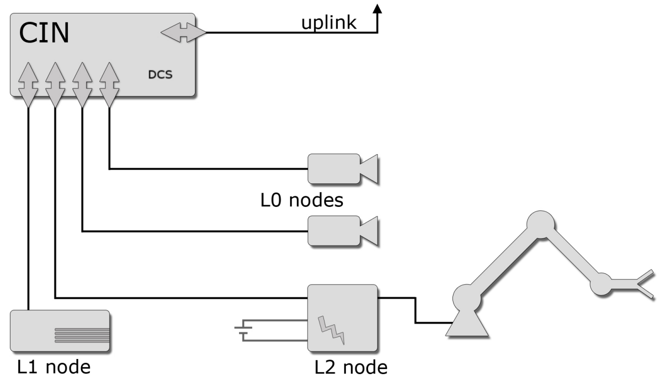


Figure 3. Network structure of the Sub-C Network (SCN)

for the scene recognition.

The usage of a seven degree of freedom system like the ORION 7P has several advantages. The design of the arm is in a way, that the only case for a singularity is when the wrist is parallel to the lower arm. This case can be detected easily, allowing a geometric approach for the inverse kinematic problem. Since the control of the manipulator provided by Schilling Robotics only offers position control, a classical point-to-point trajectory generation scheme can and must be used. This simplifies the manipulator control by far and allows for more time in the image processing part. The only problem that can arise is, that the manipulator is not fast enough for the grasping task in a dynamic environment.

### The Sub-C Network

We will keep the system as modular as possible to allow easy adaptation to different UUVs (unmanned underwater vehicles). For data exchange between modules we have outlined a system which uses a ethernet link together with a power connection in one standard 6-pin plug. The system named Sub-C Network (SCN) resembles the common structure of an ethernet network and extends it with certain abilities to improve reliability and ease of use.

See fig. 3 for an overview. The basic guidelines of the design can be summarized as follows:

1. Use of standard ethernet components
   (a) High availability
   (b) High reliability
   (c) High interoperability between components of different vendors
   (d) Low cost
2. Use of standardized mechanical components
   (a) E.g. use of a single 6-pin standard plug for all modules

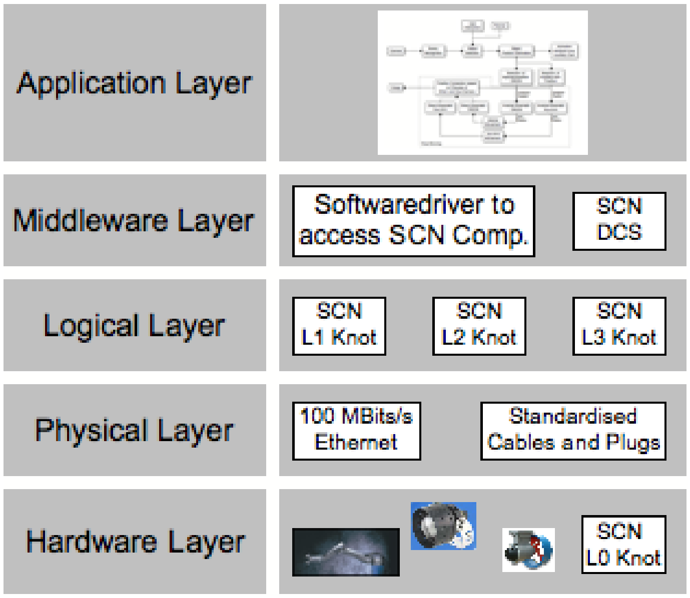


Figure 4. SCN (within the structure of a robot control system)

3. Use of a standardized software interface (XML over TCP/IP)
    (a) With sufficient flexibility to handle a wide variety of modules
    (b) Yet small enough to be implementable on microcontrollers

SCN as itself is a hardware organization system. It serves the means to control all the subsystem of an underwater vehicle and standardises the plugs and communication interface. SCN ends at the point where the middleware framework of the robotic system begins and offers all necessary drivers to communicate with the management system and the sub components like cameras, manipulators etc. (see figure 4).

**Network Structure.** The main component of the network is the central interconnection node (CIN). The CIN consists of an ethernet switch, a power supply and a device control service (DCS) hosted on an embedded computer. The devices connected to the CIN have to register themselves at the DCS via a XML based protocol and have to provide periodic status information to the DCS during runtime. This information can be requested from the DCS by any system connected to the network. Furthermore the DCS can control the power state of each device using the power connection included in the standard plugs. Small devices can be directly powered by the power supply of the CIN, devices with higher current consumption have their own power supply and use the power connection of the SCN just as a control signal when to power up or down. A total of four different types of nodes can be present in a SCN:

1. Basic nodes (level 0)
    (a) Systems without additional computational resources regarding the SCN
    (b) Power supply over the 6-pin standard plug
    (c) E.g.: camera systems, light, ...
2. Intelligent nodes (level 1)
    (a) The system is "‘SCN aware"’ → automatic registration at the DCS
    (b) Power supply over the 6-pin standard plug
    (c) E.g.: image processing nodes, IMUs, ...
3. High energy nodes (level 2)
    (a) The system is "‘SCN aware"’ → automatic registration at the DCS
    (b) Power supply over a separate feed line
    (c) On/off state is controlled via the power lines of the 6-pin standard plug
    (d) E.g.: manipulator control, thruster control, ...
4. Central interconnection nodes (level 3)
    (a) Contains an ethernet switch
    (b) Central power supply for level 0 and level 1 nodes
    (c) Device control service hosted on an embedded computer
    (d) Cascadable

**Device Control Service.** The device control service running on the CIN plays a central role in coordinating the single nodes on the network. Besides providing standard network services (e.g. DHCP) the DCS is also able to control the power supply of every node. Thus the DCS can switch off single nodes in the network to conserve power. Furthermore the DCS provides status information on all available nodes in the network, e.g. an image processing node could ask the DCS about the available camera nodes.
Since the CIN is cascadable like any standard ethernet switch the main features of ethernet networks remain:

1. Transparency between the different devices of the system
    (a) Dynamic rerouting of data streams between devices (e.g. camera systems, control systems, computer vision systems)
    (b) Dynamic switching to backup systems in case a system fails
2. Seamless data transfer into WANs over secure network connections
    (a) Direct transfer of measurement results or detected anomalies
    (b) Engage control over great distances

**Dedicated Hardware.** The camera systems will use industrial digital cameras equipped with a GigE Vision interface. The data processing systems will house high-efficient and rugged embedded Pentium M systems. The processing systems can either be dedicated to a single task, e.g. manipulator control, or can be used as general purpose systems which can be dynamically assigned to certain processing tasks. Using such standardized and flexible components helps to improve the system's reliability and ease of use.

## MODES OF OPERATION - DUAL USAGE

The system will be usable in a semi- or fully-autonomous mode.

In the first case it can be used as an autopilot for a manipulator attached to a ROV, in the second it can be used in AUVs to enhance their usability in inspection/maintenance tasks of underwater structures.

In the autopilot mode, an operator will be able to see the scene in front of the manipulator and can choose between objects identified by the scene recognition. These objects will be highlighted in the scene and can be chosen for further actions, e.g. grasping/storing or other action which will be defined in the course of the project. The goal for the autopilot mode is to reduce the manipulation task to supervision only, the developed autonomous controller will deal with all disturbances from the environment or due to varying motion of the carrier platform.

In the second case, fully-autonomous mode, the system can be preprogrammed with a plan to fulfill certain tasks at certain events. An event is a external trigger, e.g. the AUV arrived at a certain position. Then a task linked to this event will be executed. For example the event "Arrived at Location xy" is triggered by the AUV navigation system and the Task "Grasp a cylindrical object of type a"(for example transponders) is linked to this event. As soon as the event fires, the C-Manipulator system will wake up, start a scene recognition and identifying the predefined objects of type a, if any can be found in front of the stereo camera system. If the object is found the grasping process as described above is executed. Success or Failure (e.g. no object found) is transmitted to the C-Manipulator planer, which can communicate this through an additional interface to the global mission planer of the AUV. This would allow, for example in the case, that no object was found, to re-plan on the AUV level (e.g. searching for the correct location). This replanning on the AUV level is not addressed by the C-Manipulator project.

## PLANNED TESTS

To achieve the described goals, we will continually test our system during the development. We will implement and test the system in an specially designed indoor underwater tank. This tank will comprise a gantry crane on top of the rim enabling simulation of carrier vehicle motions in order to test the robustness of the developed control approaches under dynamically changing conditions. Therefore, we will program the gantry crane to move in trajectories which have a similarity to real ROV/AUV trajectories. The design of the underwater test bed is shown in fig. 5. The test bed will be fully functional by June 2007.

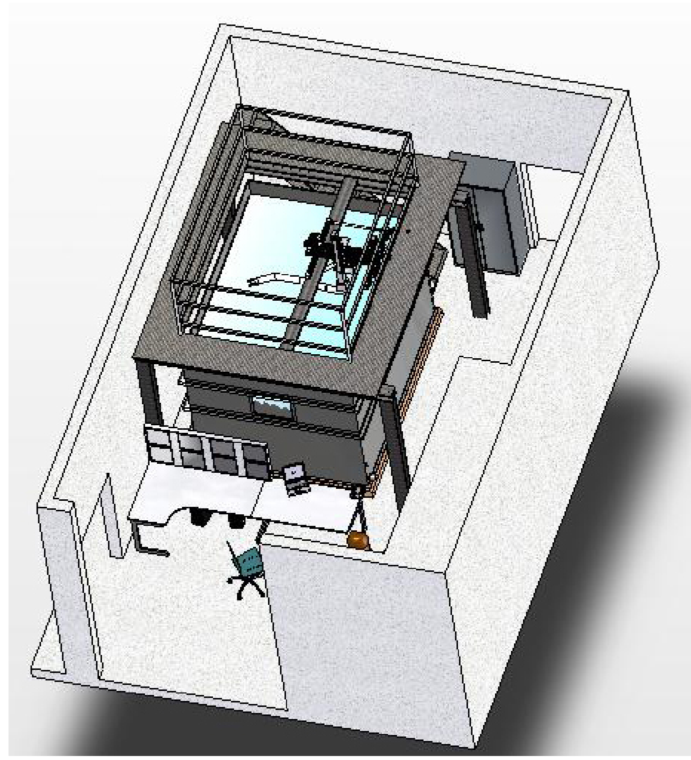

Figure 5. The DFKI Underwater Test-Bed

Furthermore, we plan to integrate a force sensor at the connection between the carrier (gantry crane) and the manipulator to study and reduce the occurring interlinking forces (hydrodynamic effects).

Furthermore, in the tank we will test the system under different light and water conditions (varied levels of maritime snow, floating objects) and adapt our vision algorithms to these conditions in order to cover a large field of possible locations and underwater conditions for future applications.

Other interesting disturbances we would like to study are, the behavior under different current condition and the changes due to decay or impurities on the manipulator and the sensors

As the final and most realistic test, we will use our manipulator system in the Baltic Sea performing autonomous pick-and-place operations on the sea ground. As a carrier platform we will use the wheeled underwater vehicle MOVE (MARUM, University of Bremen) [5].

Figure 6. THE MOVE Vehicle (c) marum, University of Bremen, Germany

## EXPECTED RESULTS

We expect, that in a first phase, till middle of 2008, C-Manipulator will be able to detect and grasp objects in a stationary set-up, which means using a fixed base with no disturbances from the carrier platform or due to poor visibility. Then in phase 2, we will test it under dynamically changing conditions and optimize it in order to use it in as many realistic situations as possible. Thus, we expect that after 3 years (in 2009) we will have a full operating system which will enhance the capabilities of existing ROVs and AUVs.

## ACKNOWLEDGMENT

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