Sensorless Computer Control of an Underwater DC Manipulator

Jochen Kerdels
Underwater Robotics Department
DFKI-Lab Bremen
Germany, 28359 Bremen
Email: jochen.kerdels@dfki.de

Jan Albiez

Frank Kirchner

***Abstract*—Virtually all manipulators used on todays underwater remote operated vehicles (ROV) are controlled manually by human operators. Thus, extensive sensory information about speed, position and load for the different joints of the actuator are often not needed. Especially the dc-manipulators on small- and middle-class ROVs often offer no sensory information at all. Given that we use such a dc-manipulator among others in a research project dealing with computer controlled autonomous underwater manipulation, we needed the speed and position information and an estimation of the force applied by the manipulator, especially of the gripper. As the refit of an existing underwater manipulator with additional sensors is quite challenging and error-prone, we developed a sensorless control for the dc-manipulator based on the back EMF of the acutators.**

I. INTRODUCTION

The dc-manipulator systems typically used on small- or middle-class ROVs come without any sensory systems which could provide position or speed feedback. They are intended to be used directly by a human operator who controls the robotic arm just by visual inspection. However, if such a manipulator system has to be controlled by a computer to manipulate things autonomously or to provide computer-assistance to the operator, some information about the actual speed and position of the joints is needed. Furthermore, information about actual speed and power can be used to estimate the current force applied by the manipulator and thus can be used to manipulate objects very carefully.

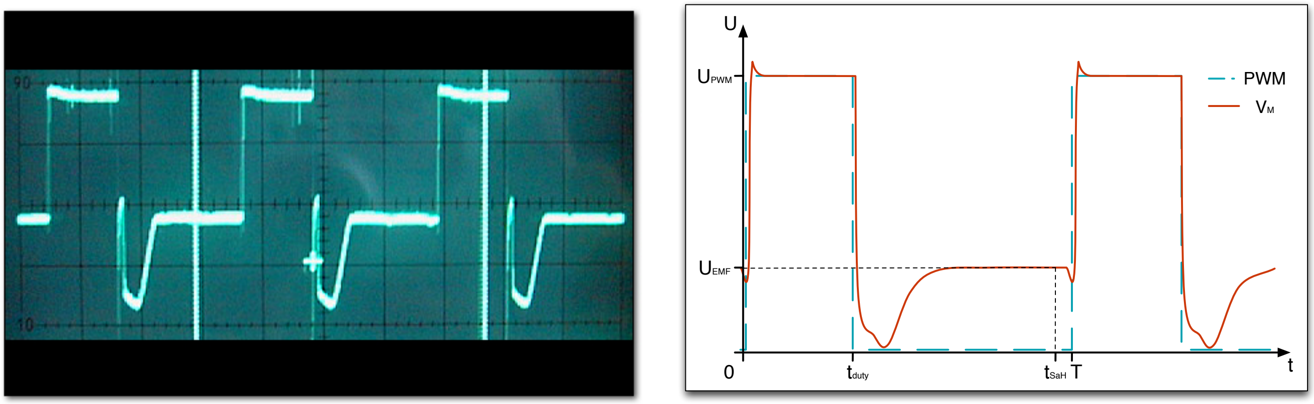
Even though it seems to be not impossible to refit a robotic arm with proper position or speed sensors on every joint, this procedure would be quite complicated, expensive and error-prone, especially if the robotic arm is an underwater system which implies additional complications with respect to sealing issues. In this paper we present a solution to this problem by using the dc-motors of the robotic arm themselves as sensors. This method, called ”Back EMF control”, uses the current induced by the motors to measure the actual rotating speed of the motor shaft and allows for precise control of the motor speed and, by integrating, control of the particular joint position. In Addition, by monitoring the needed power to provide a certain speed, an obstruction of the robotic arm or an object inside the gripper can be detected. This kind of measurement is inherently safe and robust, as it is directly using the motors as sensors. Only when a motor fails, the sensor fails too and in such a situation, the sensor failure is the least problem. Surprisingly, the back EMF control approach is not used very widely. The most common use is sensorless control of brushless dc-motors [4]. In the field of mobile robotics the approach is used by the group of Illah Nourbakhsh at CMU to build low cost educational robots [5][6].

We demonstrate this technique on the 123 DC-Manipulator by sub-Atlantic.

II. BACK EMF REVISITED

In general, back EMF is defined as ”the electromagnetic field that opposes the normal flow of current in a circuit”. In the case of motor control, every dc-motor can also be seen as a generator which provides a voltage at its terminals when the shaft of the motor is rotating. The generated voltage is proportional to the speed and thus can be used to measure the rotational speed of the shaft. It may seem contradictory to measure the voltage at the motor terminals while simultaneously driving the motor with an external voltage, but these two processes can be separated from each other. The key is to use a pulse width modulation (PWM) to drive the motor where the voltage applied the motor is set by the ratio between the high and low phases (duty cycle) of a square wave. During the low phase of this signal, no voltage is applied to the motor and the voltage generated by the motor can be measured. This measurement should take place just before the end of the low phase, as in its beginnings a spike from the motor coils is present too. The voltage which can be expected at the terminals depends on the type of motor, but is in general lower than the voltage used to drive the motor.

Fig. 1 depicts the voltage characteristic at the motor terminals while a PWM signal with 33% duty cycle is applied, where fig. 1a shows an oscilloscope image and fig. 1b shows the corresponding graph of the voltage characteristic. After the high phase of the PWM signal at time t_{duty}, the spike caused by the motor coils is clearly visible. Due to this spike, the measurement of the back EMF U_{EMF} schould take place as late as possible during the subsequent low phase at time t_{SaH}. In the first place, the late measurement ensures the least interference with the spike at the beginning of the low phase, secondly it allows for a duty cycle as large as possible. As we



(a)

(b)

Fig. 1: The voltage characteristic at the motor terminals while a PWM signal with 33% duty cycle is applied.

need at least some low phase duration for our measurement, it is obvious that a 100% duty cycle of the PWM signal is not possible when using back EMF control. In our setup the maximum usable duty cycle was 75%. To compensate for the loss of power caused by this restriction, a higher input voltage can be used, e.g. a 24 volt system would be driven with a 32 volt input if the maximum usable duty cycle is 75%.

To be able to measure the back EMF, the used H-bridge driver which drives the dc-motor must not short circuit the output during the low phase of the PWM. This is sometimes done to enhance the precision of the driver or to implement a motor break. In case of back EMF control, the short circuit would erase the back EMF signal completely.

III. APPLICATION TO THE 123 DC-MANIPULATOR

We developed a prototype of a electronic control board which uses the previously described back EMF approach to control the 3 axis 123 dc-manipulator by sub-Atlantic [1]. Besides a general proof of concept of this approach for the control of an underwater manipulator system, we already layed out the basic design concepts for a future controller in the actual prototype system:

- No modification of the dc-manipulator is needed.
- Control of speed, position and an estimation of the force applied by the manipulator.
- The modular design ensures the extensibility to an arbitrary number of axis.
- The flexible interface allows for various control systems, ranging from common hand controllers to networked computer control.
- A robust and fail safe electronic architecture.

In the following subsections the different components of the prototype system are described. The section closes with a discussion of the control characteristics of the system and the results obtained with the prototype system.

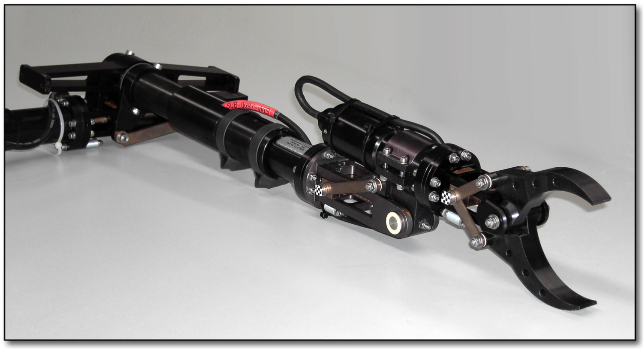


Fig. 2: The 123 dc-manipulator by sub-Atlantic which was used in our experimental setup.

A. *123 DC-Manipulator*

The 123 dc-manipulator by sub-Atlantic is a 3 degrees of freedom (DOF) underwater manipulator system (fig. 2) rated for a depth of $300m$. Each DOF is actuated by a dc-motor $24V$ ($1.2A$ max.) connected to a spindle drive. As this manipulator is intended for underwater use it has a proper sealing of the used dc-motors which makes it quite difficult to refit each dc-motor with an encoder without damaging the sealing of the system. Given that we use this manipulator in a research project dealing with computer controlled autonomous underwater manipulation, we needed the speed and position information and an estimation of the force applied by the manipulator, especially of the gripper. This circumstances led to the back EMF approach.

B. *Electronics*

The electronics used to demonstrate the back EMF control approach is shown in fig. 3. The prototype board supports the back EMF control of up to 5 dc-motors. For each motor a separate microcontroller unit reads the back EMF voltage and generates the PWM signal send to the motor driver IC. The used microcontroller on each unit is an ATMEGA168 by

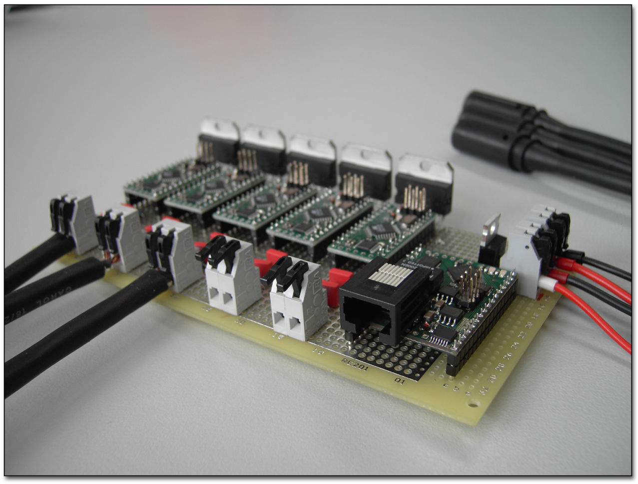


Fig. 3: The control electronic prototype used to demonstrate the back EMF control approach on the 123 dc-manipulator by sub-Atlantic.

Atmel and the motor driver IC is a L6203 by STMicroelectronics. These joint control modules are connected via an I^2C bus to a central microcontroller module with ethernet capabilities as communication interface. Each joint module continously reports the actual position, speed and an estimation of the force to the central module. The central module itself forwards this information to the particular receiver in the network. In the opposite direction the central module receives new position and speed commands for the different joints from a sender in the network and dispatches these commands to the respective joint modules. It is important to note, that no part of the computation needed for the direct control of the manipulator is done outside the prototype board. The network connection is just the communication interface in our special setup. It is just as well possible to build a manual hand control panel directly on top of the joint control modules, e.g. with the aibility to store a set of useful positions and to recall a particular position of this set with the press on a button when it is needed needed.

On each joint module the microcontroller uses its built-in analog-to-digital converter (ADC) to measure the back EMF of the particular joint.The used ATMEGA168 has an integrated 10 bit ADC which can be clocked with 200kHz. If a higher sample rate is needed, the ADC can be clocked faster, but with the drawback of a lowered resolution. The complete conversion takes 13 ADC clock cycles (65 s at 200kHz). This means, that would the whole conversion take place at the end of the low phase of the PWM signal, the PWM signal would has to have a very low frequency or the maximum possible duty cycle would be very low. Examining the conversion process in more detail reveals, that the time which is needed to measure the back EMF at the end of the low phase can be reduced significantly. Actually, the conversion inside the microcontroller is done in two steps. A *sample and hold* step at the beginning of the conversion makes a "copy" of the input signal and then the analog to digital conversion is done on this copy. Fortunately the sample and hold step takes just 1.5 ADC clock cycles (7.5 us at 200kHz). Thus, only this step has to take place at the end of the low phase (see t_{SaH} in 1b). The actual conversion itself is done afterwards during the following high phase. With this ADC timing the PWM signal can be generated with an acceptable frequency of 1kHz and the maximum usable duty cycle is 75%. To be able to use a higher PWM frequency, a seperate and faster ADC should be used.

C. Software

Before a joint module can be used regularly, an automatic calibration has to be done once. With this calibration the joint module learns the characteristics of the connected actuator. For this purpose the particular joint has to have a stop position. Rotary joints can not be calibrated automatically. They have to be temporarily equipped with a block which can be removed after the calibration process. During the calibration the joint is moved several times back and forth, each time controlled to a different, but constant back EMF signal. For every complete movement the inverse of the number of PWM cylces needed for this movement is saved to a lookup table. This lookup table is later used to determine the relative movement the joint has made when a specific back EMF signal is measured. Integrating these relative movements results in the absolute position of the joint at any one time.

A second lookup table is built up simultaneously. It provides information about which duty cycle of the PWM signal is needed to provide a certain speed at a certain position of the particular joint. With this information a deviation of the PWM duty cycle from the expected value can be detected, e.g. if an object is picked by the gripper or the joint is obstructed. In some cases, depending on the actuator, it may be sufficient to store only the average PWM duty cycle for the different speeds. In hour setup however, this is not the case. Due to the geometric design of the used actuators, the load on the dc-motor depends on the actual joint position. Therefore a lookup table which reflects these changing loads has to be used when controlling the 123 dc-manipulator of sub-Atlantic.

After the calibration process has finished, the lookup tables are stored into the non-volatile EEPROM of the joint module microcontroller and they are reloaded every time the microcontroller is switched on. In our setup, the calibration of the whole 123 dc-manipulator takes about two hours. As this calibration has only to be done once for any manipulator system, the relatively long calibration time seems passable.

During regular operation the information about the absolute position of a joint tends to drift as it is derived by the integration of the directly measured speed. The next subsection covers this subject in more detail. From the software point of view the drift can be handled in different ways. The straight forward solution is to reset the absolute position every time the particular joint is at a stop position, e.g. if the gripper is fully opened, such a reset could occur for this joint. An extension to this solution is to measure the actual drift each time a reset is done at a stop position and to use this data

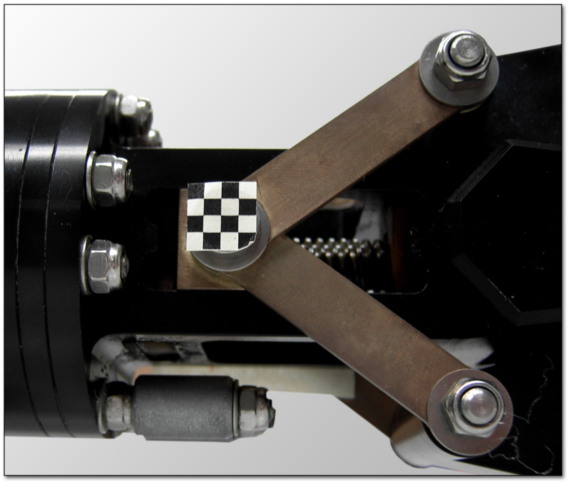


Fig. 4: In order to measure the movements of the arm externally, a marker was attached at every joint and tracked with a camera.

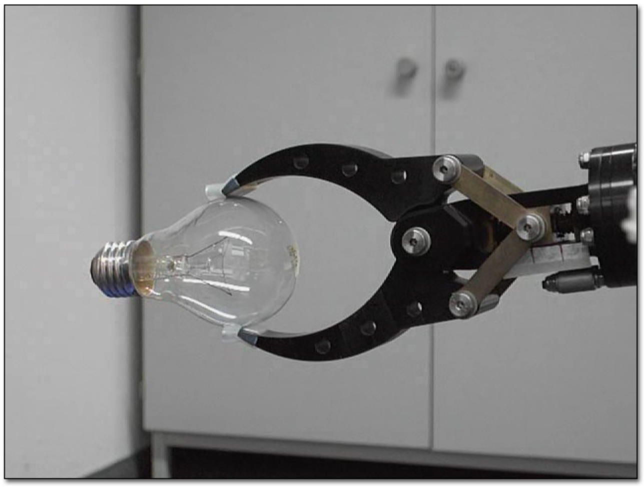


Fig. 6: Gripping a lightbulb demonstrates the degree of sensitiveness which can be achieved with back EMF force control.

to calculate the average drift per PWM cycle which could be then substracted from the position integral at each integration step. In addition, the average drift per PWM cycle could be smoothed with an exponentiell smoothing, arguing that the drift is influenced by the actual operating conditions and that the latest operating conditions will be the best estimate for the near future operating conditions.

D. *Control Characteristics*

As described in the last section, the information about the absolute position of a joint tends to drift. To further investigate this drift, a method to externally measure the absolute position of a joint was implemented. To measure the position, a marker was placed on the skid of the spindle drive (fig. 4) of the particular joint and a camera was used to measure the position of the marker. The upper row in fig. 5 shows the absolute positions of the three joints of the 123 dc-manipulator during the calibration phase. It can be seen, how the speed of the joints decreases over time. Since the joints are driven forth and back between their stop positions, no drift ist visible during calibration. Contrary, the drift is clearly visible in the lower row of fig. 5 where the joints are tracked during normal operation. For this test the joints moved between four different positions with two different speeds over and over again. The biggest drift which was measured was the drift of the wrist joint. The position was shiftet by 0.1% of the traverse path length per position changed. The second biggest drift was measured for the elbow with 0.08% of the traverse path length. The least drift had the gripper with only 0.013% of the traverse path length. The relatively constant drift suggests that the drift could be compensated quite well with the methods desribed in III-C.

Contrary to the absoulte position which is derived by integration, the speed is linearly proportional to the measured back EMF signal. The back EMF signal measured has relatively low noise and thus the speed can be controlled very precisely. What is most surprising, this holds true even for very low speeds. In our experiments the skid of the spindle drive could be moved as slow as $1.5mm$ per second. This speed control enables the dc-manipulator to carry out very precise manipulation tasks which were not possible before to such an extent.

Furthermore, with the information of the actual speed and the actual PWM duty cycle of a joint it can be estimated if the joint is in some way obstructed. Such an estimation is especially important for the gripper, as it enables the system to grasp very fragile things without damaging them. In addition, this information can be used to inform the operator of the manipulator of a possible degradation of a joint, e.g. caused by some fouling on the spindle or motor shaft. Thus protecting the manipulator system at an early stage and reducing the risk of a complete breakdown of that particular joint. As an example for the sensitiveness of this back EMF based force control we were able to grip, among other sensitive objects, a lightbulb with our system (fig. 6). This is, refering to [2] and [3], a standard test for the sensitivity of a manipulation system.

IV. CONCLUSION AND OUTLOOK

The briefly presented control approach allows for the sensorless speed and position control of nearly every DC manipulator system without any modification to the system itself. In addition, an estimation of the force exerted by the manipulator can be obtained. Besides enabling these systems to be controlled autonomously by a computer, it can also provide useful information to the operator about the actual pose of the system, if a joint is blocked or if an object was gripped. In Addition, one could imagine to provide semi-autonomous computer control in the sense of an intelligent operator assistance system.

Given the results obtained with this prototype, we plan to further investigate the back EMF control approach. In this regard we will increase the maximum possible control

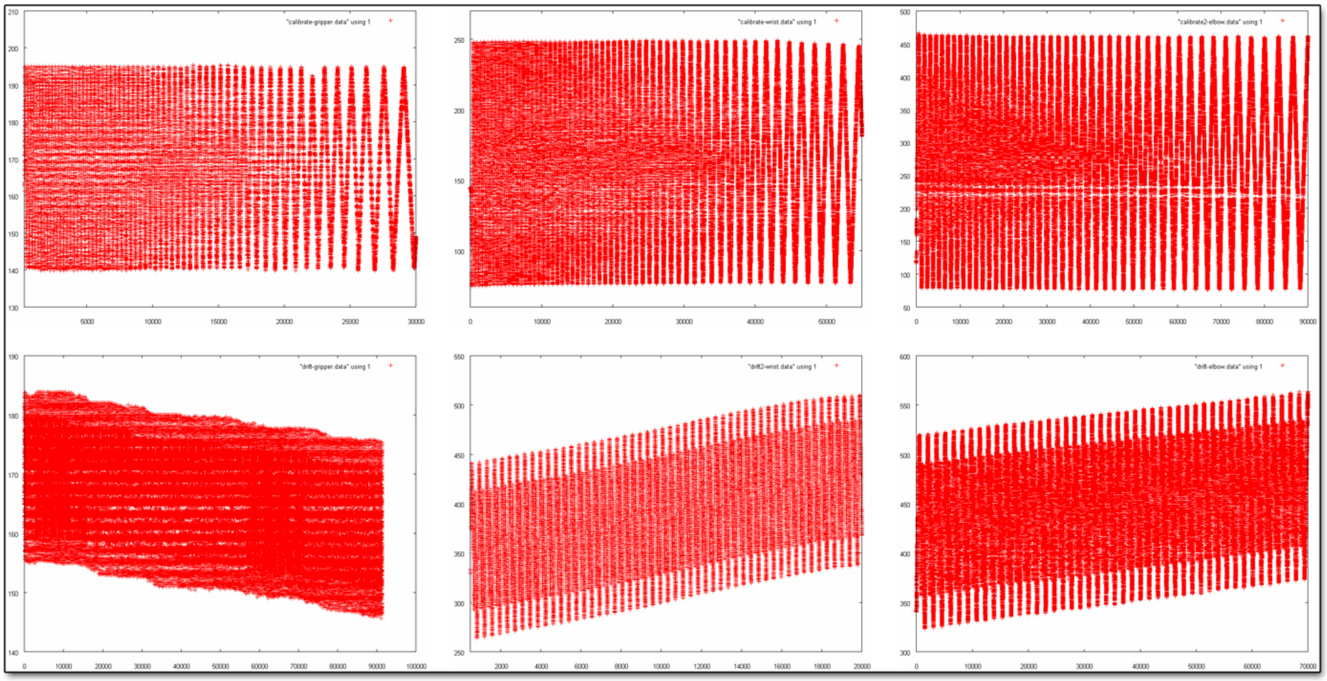


Fig. 5: Results of the external absolute position tracking with a marker (fig. 4). The upper row shows the movement of the three joints (gripper, wrist, elbow) during the calibration phase. The lower row shows the drift occuring on the joints during regular operation. As this data are aquired with a camera, the time axis has the unit *frames* and the position axis has the unit *pixels*.

frequency and the maximum possible duty cycle of the PWM signal by using dedicated analog-to-digital converters with a much higher sampling frequency than the built-in ADCs of the currently used microcontrollers. Consequential the computation has to be done on a system with more computational power, i.e. by using FPGAs or DSPs. The higher control frequency will not only provide higher accuracy and low noise, it will presumably reduce the drift error as the integration will be composed of smaller and much more precise integration steps.

REFERENCES

[1] http://www.sub-atlantic.co.uk/

[2] Zhu, X., Ding, H., Wang, J.: Grasp analysis and synthesis based on a new quantitative measure, IEEE Trans. Robotics and Automation, vol. 19, no. 6

[3] Roethling, F. : Real Robot Hand Grasping using Simulation-Based Optimisation of Portable Strategies, University of Bielefeld, Diss., 2007

[4] Shao, J.: Direct Back EMF Detection Method for Sensorless Brushless DC (BLDC) Motor Drives, Virginia Polytechnic Institute, Thesis, 2003

[5] Hsiu, T.,Richards, S., Bhave, A., Perez-Bergquist, A., Nourbakhsh, I.: Designing a Low-cost, Expressive Educational Robot, In Proceedings of IROS 2003

[6] Falcone, E., Gockley, R., Porter, E., Nourbakhsh, I.: The Personal Rover Project: The comprehensive design of a domestic personal robot, Robotics and Autonomous Systems, Special Issue on Socially Interactive Robots 42 (3-4), pp 245-258, 2003