RECYCLING A DISCARDED ROBOTIC ARM FOR AUTOMATION ENGINEERING EDUCATION

Filippo Sanfilippo*, Ottar L. Osen† and Saleh Alaliyat†
*Department of Maritime Technology and Operations, Aalesund University College,
Postboks 1517, 6025 Aalesund, Norway. Email: fisa@hials.no
†Department of Engineering and Natural Sciences, Aalesund University College
Postboks 1517, 6025 Aalesund, Norway.

KEYWORDS

PLC, automation engineering education, robotic arm.

ABSTRACT

Robotics and automation technology instruction is an important component of the industrial engineering education curriculum. Industrial engineering and automation departments must continuously develop and update their laboratory resources and pedagogical tools in order to provide their students with adequate and effective study plans. While acquiring state-of-the-art manufacturing equipment can be financially demanding, a great effort is made at Aalesund University College to provide the students with an improved hands-on automation integration experience without major capital investments. In particular, a strategy that consists of recycling electronic and robot disposals is adopted. Students are engaged in a real reverse engineering process and then challenged to find new possible applications and uses.

By adopting a pedagogical prospective, this paper introduces the design and implementation of a robot control system on a hardware platform based on a *Programmable Logic Controller* (PLC). In particular, the controlled robot is a *Sykerobot 600-5* manipulator with five degrees of freedom (DOFs) that was disposed of by the industry several years ago as electronic waste. Particular emphasis is placed on the pedagogical effectiveness of the proposed control architecture.

INTRODUCTION

Automation engineering education is a multidisciplinary field of study that involves different types of knowledge and skills. This educational field applies the discipline of mechanical systems, electronic systems, computers and control systems to the integration of product design and automated manufacturing processes. The Automation engineering program at the Faculty of Engineering and Natural Sciences and the Product and System Design program at the faculty of Maritime Technology and Operation, at Aalesund University College (AAUC), Norway, provide courses leading to Bachelor's and Master's degrees. These two study programs have several common topics concerning automation engineering subjects.

A common teaching strategy of these programs involves the ideas of Learning by Doing (LBD) (Nguyen & Graefe 2001), the approaches of Problem Based Learning (PBL) (Albanese & Mitchell 1993) and the concepts of Active Learning (AL) (Martín et al. 2010). In fact, one of the most effective ways of teaching students how to perform a useful task consists of actively involving them and letting them do it. The LBD method is not a new instructional theory, it is exactly what it sounds like. Aristotle stated: *"One must learn by doing the thing, for though you think you know it, you have no certainty until you try"*. Similarly, Confucius declared: *"I hear and I forget. I see and I remember. I do and I understand"*. More recently, John Dewey became one of the strongest proponents of the LBD approach. In (Dewey 1997), Dewey argued: *"Education is not preparation for life, it is life itself"*.

At AAUC, during their study courses, students are involved with realistic problem settings and scenarios that reflect real application prospectives (Rekdalsbakken & Sanfilippo in press). Very often, students are divided into groups that stimulate their teamwork skills and critical thinking abilities. From a social point of view, group dynamics are also relevant. In order to prepare the students for their working life, the preferred method of putting groups together is randomly, with a random leader. This method is perceived as fair by the students. Moreover, normal working conditions are simulated in which the team members are usually unable to select their own team. In addition, this approach also establishes new social networks in the classroom. Our experience is that the students perform better when they know each other well. This probably has to do with the fact that they feel safer in the learning environment and are less afraid of possibly embarrassing situations. However, in generating random groups, an attempt is made to break up the existing frozen social ties, thereby forcing the students into new roles. As such, an industry-like social situation is created.

Moreover, our students are included in research projects and innovation activities in cooperation with real companies and industry partners. In such a view, the student laboratory has a central and challenging position as an open-space workplace where students can experience hands-on automation integration training under the supervision of both their professors and the partner company engineers. The networking between students and companies allows the students to gain deeper knowledge about industry demands and challenges. The industry also gets valuable information for their recruitment processes and learns about ongoing research projects at the university. In addition to inspiring and motivating students in their studies, AAUC regularly organises several internal robotic competitions and workshop events. The best student projects are often selected to join national and international robotic contests.

A great effort is made at AAUC to provide the students with an adequate and effective automation integration experience without major capital investments. Moreover, the idea of recycling out-of-date electronic equipment and robots is promoted. Stressing the fact that after a robot has outlived its normal utility, its disposal becomes a challenge for the enterprises using it, students are challenged to find new possible applications and uses.

One of the most challenging robotics engineering tasks involves the integration of a robotic arm in material handling, assembly, and production processes. The knowledge and skills required for these kinds of tasks are purely mechatronic and therefore multidisciplinary. Emphasising the pedagogical prospective, this paper introduces the design and implementation of a robot control system on a hardware platform based on a *Programmable Logic Controller* (PLC) (Bolton 2009). The controlled arm is a *Sykerobot 600-5* manipulator with five DOFs that was disposed of by the industry several years ago as electronic waste. A master-slave architecture is set up with the controller acting as a master and the PLC as a slave. The paper analyses the drawbacks and the advantages related to the choice of standard PLCs in these kinds of applications, compared to the much more common choice of specialised hardware or industrial proprietary computers. Particular emphasis is placed on the pedagogical effectiveness of the proposed control architecture.

This paper is organised as follows. A review of the related research work is given in the second Section. In the third Section, we focus on the description of the system architecture. In the fourth Section, related results are discussed. Finally, conclusions and future works are outlined in the fifth Section.

RELATED RESEARCH WORK

AAUC has made a notable effort in order to limit the financially demanding cost of acquiring state-of-the-art manufacturing equipment. For instance, in (Liu et al. 2012), our research group presented a modular pentapedal walking robot that can be also used for pedagogical uses. Similarly, several university laboratories have followed different strategies.

One possibility consists of developing virtual laboratories and workspaces that can provide the students with an acceptable learning experience. In (Callaghan et al. 2008), for instance, the popular virtual world, *Second Life*, is used as a platform to create experiential based learning experiences in a 3-D immersive world for teaching computer hardware and electronic systems. In particular, a number of approaches to capturing, displaying and visualising real world data in such environment are implemented. The main goal of this virtual laboratory is to allow students to easily interact with a set of physical processes via the Internet. The students are able to run experiments, change control parameters, and analyse the results remotely. An additional feature of this virtual laboratory is its architecture, allowing for an easy integration of new processes for control experiments. In (Zhang et al. 2007), Zhang et. al. presented a kind of educational robotics system based on the use of *LEGO* bricks and on a newly designed input/output interface. Using this system, students can program a robot through an iconic interface environment and a normal programming language such as Java or C according to their knowledge. During this process, they learn the sensorial technology and motor-control methods. At the same time, students can overview the process using a web-camera and can interrupt it in case of malfunctions. However, the advantages and benefits enjoyed by students that work in a real physical laboratory can hardily be replaced by any virtual counterparts.

To meet the need of providing the students with a physical experience without major capital investments, general purpose open-source developing platforms could be used as pedagogical tools. In (Sarik & Kymissis 2010), Sarik and Kymissis presented a lab kit platform based on an *Arduino* microcontroller board and open hardware that enables students to use low-cost, course specific hardware to complete lab exercises at home. This somehow represents an extension of the university laboratory and gives students the possibility of improving their learning experience. However, this approach does not provide the students with a real industry-like experience.

One possible way of providing students with a real industry-like experience consists of using PLC-based developing platforms. In (Chung 1998), Chung presented a cost-effective approach for the development of an integrated PC-PLC-Robot system for industrial engineering education. This work shows that even though many universities do not have the financial resources to acquire state-of-the-art manufacturing systems, they can still provide their students with an adequate and effective integration training with existing equipment. Our approach in this paper, follows the same idea, emphasising the effectiveness from an educational point of view.

SYSTEM ARCHITECTURE

The controlled robot is a *Sykerobot 600-5* manipulator with five DOFs. This robot was disposed of by one of our industry partners several years ago as electronic waste. Since this manipulator is obsolete, it is relatively hard for students to find any related works. This fact is particularly relevant from a pedagogical point of view because it forces students to get thoroughly exposed to the subject and involves them in a real reverse engineering process. Moreover, since the original controller cabinet of the robot is missing, each group of students need to develop its own control architecture. According to the teacher's experience, the most promising system solution developed by the students is presented in the following of this paper.

The system architecture is shown in Fig. 1. By using the *Modbus* protocol (Modbus 2004), a master-slave architecture is set up with the controller acting as a master and the PLC as a slave. The control software is fully developed on a commercial PLC system, using its standard programming tools and the multi-tasking features of its operating system. The input device is connected to the computer through the serial USB channel. In the next subsections, the different components of the system are described.

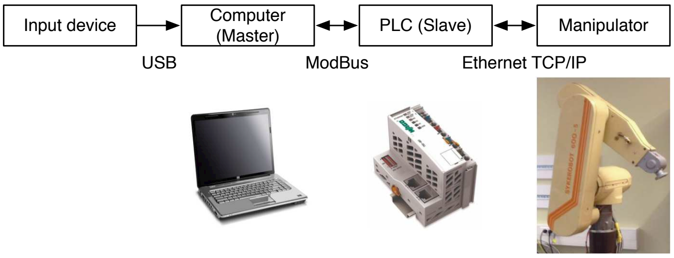

Fig. 1. The proposed control system architecture: a master-slave architecture with the controller acting as a master and the PLC as a slave.

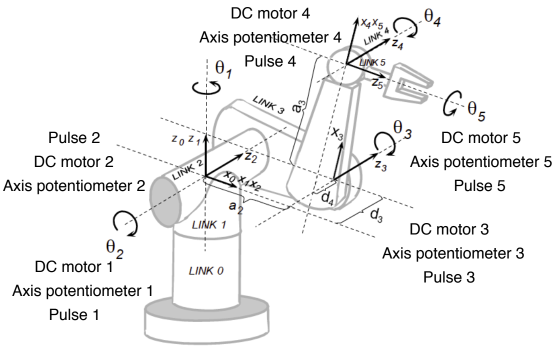

Fig. 2. The *Sykerobot 600-5* manipulator with 5 DOFs.

The Control Algorithm

The kinematic sketch of the *Sykerobot 600-5* is shown in Fig. 2. A good exercise for students consists of finding the kinematic model of the arm. Students learn about the use of geometric transformations, also called rigid transformations, to describe the movement of components in a mechanical system. These transformations simplify the derivation of the equations of motion, and are central to dynamic analyses.

According to the frame assignments in Fig. 2, the Denavit-Hartenberg (D-H) tables (Denavit 1955) of the *Sykerobot 600-5* is shown in Table I. Substituting the DH parameters into the following general homogeneous transformation (HT) matrix,

$$ {}^{i_1}_{i-}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (1) $$

where s stands for *sin* and c for *cos*, the relative HT matrices for the manipulator can be obtained:

$$ {}^0_1T = \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (2) $$

$$ {}^1_2T = \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s\theta_2 & -c\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (3) $$

$$ {}^2_3T = \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & a_2 \\ s\theta_3 & c\theta_3 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (4) $$

TABLE I. D-H TABLE OF THE *Sykerobot 600-5*, WHERE $a_2 = 0.33m$, $a_3 = 0.27m$, $d_3 = 0.20m$ AND $d_4 = 0.09m$

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	$-\frac{\pi}{2}$	0	0	θ_2
3	0	a_2	d_3	θ_3
4	0	a_3	$-d_4$	θ_4
5	$-\frac{\pi}{2}$	0	0	θ_5

$$ {}^3_4T = \begin{bmatrix} c\theta_4 & -s\theta_4 & 0 & a_3 \\ s\theta_4 & c\theta_4 & 0 & 0 \\ 0 & 0 & 1 & -d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5) $$

$$ {}^4_5T = \begin{bmatrix} c\theta_5 & -s\theta_5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s\theta_5 & -c\theta_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (6) $$

Since the two joint axes of the arm's wrist intersect in a single point, it is useful to consider arm and wrist separately. Thus, the arm part is defined as the part of the manipulator that contributes to the position of the wrist, while the wrist only changes its orientation (the wrist itself does not affect the position). In this case, the arm part consists of links $0-3$ and a part of the link 4. Since the wrist does not have any length parameters ($a_4 = d_5 = 0$), its relative HT matrix only has pure rotations. Consequently the HT matrix of the arm is:

$$ T_A = {}^0_1T\,{}^1_2T\,{}^2_3T\,Screw(e_1, \alpha_3, a_3)Trans(e_3, -d_4), \quad (7) $$

where $Screw(e_1, \alpha_3, a_3)$ represents the *Screw* of the reference frame $\{4\}$, while $Trans(e_3, -d_4)$ is the translation of the same reference frame along z_3 by $-d_4$. After multiplying the parts, we can get the forward kinematic (FK) equations. In detail, the arm rotation and position matrices, R_A and p_A respectively, are calculated:

$$ R_A = \begin{bmatrix} c(\theta_2+\theta_3)c\theta_1 & -s(\theta_2+\theta_3)c(\theta_1) & -s\theta_1 \\ c(\theta_2+\theta_3)s\theta_1 & -s(\theta_2+\theta_3)s(\theta_1) & c\theta_1 \\ -s(\theta_2+\theta_3) & -cos(\theta_2+\theta_3) & 0 \end{bmatrix}, \quad (8) $$

$$ p_A = \begin{bmatrix} d_4 s\theta_1 - d_3 s\theta_1 - a_3(c\theta_1 s\theta_2 s\theta_3 - c\theta_1 c\theta_2 c\theta_3) + a_2 c\theta_1 c\theta_2 \\ d_3 c\theta_1 - a_3(s\theta_1 s\theta_2 s\theta_3 - c\theta_2 c\theta_3 s\theta_1) - d_4 c\theta_1 + a_2 c\theta_2 s\theta_1 \\ -a_3 s(\theta_2+\theta_3) - a_2 s(\theta_2) \end{bmatrix}. \quad (9) $$

Up to this point, the forward position equations relating joint positions and end-effector positions and orientations have been derived. In the following, the velocity relationships, that relate the linear and angular velocities of the end-effector (or any other point on the manipulator) to the joint velocities are derived. Mathematically, the FK equations define a function between the space of Cartesian positions and orientations and the space of joint positions. The velocity relationships are then determined by the Jacobian of this function. The Jacobian is a matrix-valued function and can be thought of as the vector version of the ordinary derivative of a scalar function. The Jacobian matrix is one of the most important pieces of information in the analysis and control of robot motion.

The robot considered presents only spherical joints, therefore, the description of the angular velocity, ${}^{i+1}\omega_{i+1}$, of link $i+1$ can be obtained as:

$$ {}^{i+1}\omega_{i+1} = {}^{i+1}_{i}R\,{}^{i}\omega_i + \dot{\theta}_{i+1}\,{}^{i+1}\hat{z}_{i+1}, \quad (10) $$

where ${}^{i+1}_{i}R$ is the rotation matrix of frame $\{i\}$ with respect to $\{i+1\}$, ${}^{i}\omega_i$ is the angular velocity of frame $\{i\}$, $\dot{\theta}_{i+1}$ is the angular velocity of joint $i+1$ and ${}^{i+1}\hat{z}_{i+1}$ is the unit vector of frame $\{i+1\}$. Similarly, the corresponding relationship for the linear velocity, ${}^{i+1}v_{i+1}$, of link $i+1$ is given by:

$$ {}^{i+1}v_{i+1} = {}^{i+1}_{i}R({}^{i}v_i + {}^{i}\omega_i \times {}^{i}P_{i+1}), \tag{11} $$

where ${}^{i}v_i$ is the linear velocity of frame $\{i\}$ and ${}^{i}P_{i+1}$ is the position of frame $\{i+1\}$ respect to $\{i\}$. Applying these equations successively from link to link, we can compute ${}^{N}\omega_N$ and ${}^{N}v_N$, the rotational and linear velocity of the last link. For the considered arm, we get:

$$ {}^{1}\omega_1 = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 \end{bmatrix}, {}^{1}v_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \tag{12} $$

$$ {}^{2}\omega_2 = \begin{bmatrix} -\dot{\theta}_1 s\theta_2 \\ -\dot{\theta}_1 c\theta_2 \\ \dot{\theta}_2 \end{bmatrix}, {}^{2}v_2 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \tag{13} $$

$$ \begin{aligned} {}^{3}\omega_3 &= \begin{bmatrix} -\dot{\theta}_1 c\theta_2 s\theta_3 - \dot{\theta}_1 c\theta_3 s\theta_2 \\ \dot{\theta}_1 s\theta_2 s\theta_3 - \dot{\theta}_1 c\theta_2 c\theta_3 \\ \dot{\theta}_2 + \dot{\theta}_3 \end{bmatrix}, \\ {}^{3}v_3 &= \begin{bmatrix} s\theta_3(a_2\dot{\theta}_2 + d_3\dot{\theta}_1 s\theta_2) - d_3\dot{\theta}_1 c\theta_2 c\theta_3 \\ c\theta_3(a_2\dot{\theta}_2 + d_3\dot{\theta}_1 s\theta_2) + d_3\dot{\theta}_1 c\theta_2 s\theta_3 \\ a_2\dot{\theta}_1 c\theta_2 \end{bmatrix}, \end{aligned} \tag{14} $$

$$ \begin{aligned} {}^{4}\omega_4 &= \begin{bmatrix} -\dot{\theta}_1 c\theta_2 s\theta_3 - \dot{\theta}_1 c\theta_3 s\theta_2 \\ \dot{\theta}_1 s\theta_2 s\theta_3 - \dot{\theta}_1 c\theta_2 c\theta_3 \\ \dot{\theta}_2 + \dot{\theta}_3 + \dot{\theta}_4 \end{bmatrix}, \\ {}^{4}v_4 &= \begin{bmatrix} a_2\dot{\theta}_2 s\theta_3 - d_3\dot{\theta}_1 c(\theta_2+\theta_3) + d_4\dot{\theta}_1 c(\theta_2+\theta_3) \\ a_3\dot{\theta}_2 + a_3\dot{\theta}_3 + a_2\dot{\theta}_2 c\theta_3 + d_3\dot{\theta}_1 s(\theta_2+\theta_3) - d_4\dot{\theta}_1 s(\theta_2+\theta_3) \\ a_2\dot{\theta}_1 c\theta_2 + a_3\dot{\theta}_1 c(\theta_2+\theta_3) \end{bmatrix}. \end{aligned} \tag{15} $$

To find these velocities with respect to the non-moving base frame, they can be rotated by using the rotation matrix R_A:

$$ \begin{aligned} {}^{0}_{4}v &= R_A {}^{4}v_4 = \begin{bmatrix} {}^{0}_{4}v_{1,1} \\ {}^{0}_{4}v_{2,1} \\ {}^{0}_{4}v_{3,1} \end{bmatrix}, \\ {}^{0}_{4}v_{1,1} &= d_4\dot{\theta}_1 c\theta_1 - d_3\dot{\theta}_1 c\theta_1 - a_2\dot{\theta}_1 c\theta_2 s\theta_1 \\ &\quad -a_2\dot{\theta}_2 c\theta_1 s\theta_2 - a_3\dot{\theta}_1 c\theta_2 c\theta_3 s\theta_1 - a_3\dot{\theta}_2 c\theta_1 c\theta_2 s\theta_3 \\ &\quad -a_3\dot{\theta}_2 c\theta_1 c\theta_3 s\theta_2 - a_3\dot{\theta}_3 c\theta_1 c\theta_2 s\theta_3 - a_3\dot{\theta}_3 c\theta_1 c\theta_3 s\theta_2 \\ &\quad +a_3\dot{\theta}_1 s\theta_1 s\theta_2 s\theta_3, \\ {}^{0}_{4}v_{2,1} &= d_4\dot{\theta}_1 s\theta_1 - d_3\dot{\theta}_1 s\theta_1 - a_2\dot{\theta}_2 s\theta_1 s\theta_2 \\ &\quad +a_2\dot{\theta}_1 c\theta_1 c\theta_2 + a_3\dot{\theta}_1 c\theta_1 c\theta_2 c\theta_3 - a_3\dot{\theta}_1 c\theta_1 s\theta_2 s\theta_3 \\ &\quad -a_3\dot{\theta}_2 c\theta_2 s\theta_1 s\theta_3 - a_3\dot{\theta}_2 c\theta_3 s\theta_1 s\theta_2 - a_3\dot{\theta}_3 c\theta_2 s\theta_1 s\theta_3 \\ &\quad -a_3\dot{\theta}_3 c\theta_3 s\theta_1 s\theta_2, \\ {}^{0}_{4}v_{3,1} &= -a_2\dot{\theta}_2 c\theta_2 - a_3\dot{\theta}_2 c(\theta_2+\theta_3) - a_3\dot{\theta}_3 c(\theta_2+\theta_3). \end{aligned} \tag{16} $$

As such, the time derivative of the kinematics equations yields the *Jacobian* matrix of the arm, which relates the joint rates to the linear and angular velocity:

$$ \begin{aligned} J &= \begin{bmatrix} J_{1,1} & J_{1,2} & J_{1,3} \\ J_{2,1} & J_{2,2} & J_{2,3} \\ J_{3,1} & J_{3,2} & J_{3,3} \end{bmatrix}, \\ J_{1,1} &= d_4 c\theta_1 - d_3 c\theta_1 - a_2 c\theta_2 s\theta_1 - a_3 c\theta_2 c\theta_3 s\theta_1 \\ &\quad +a_3 s\theta_1 s\theta_2 s\theta_3, \\ J_{1,2} &= -a_2 c\theta_1 s\theta_2 - a_3 c\theta_1 c\theta_2 s\theta_3 - a_3 c\theta_1 c\theta_3 s\theta_2, \\ J_{1,3} &= -a_3 c\theta_1 c\theta_2 s\theta_3 - a_3 c\theta_1 c\theta_3 s\theta_2, \\ J_{2,1} &= d_4 s\theta_1 - d_3 s\theta_1 + a_2 c\theta_1 c\theta_2 + a_3 c\theta_1 c\theta_2 c\theta_3 \\ &\quad -a_3 c\theta_1 s\theta_2 s\theta_3, \\ J_{2,2} &= -a_2 s\theta_1 s\theta_2 - a_3 c\theta_2 s\theta_1 s\theta_3 - a_3 c\theta_3 s\theta_1 s\theta_2, \\ J_{2,3} &= -a_3 c\theta_2 s\theta_1 s\theta_3 - a_3 c\theta_3 s\theta_1 s\theta_2, \\ J_{3,1} &= 0, \\ J_{3,2} &= -a_2 c\theta_2 - a_3 c(\theta_2+\theta_3), \\ J_{3,3} &= -a_3 c(\theta_2+\theta_3). \end{aligned} \tag{17} $$

PLC

Since the discarded robot is missing the controller cabinet, students are encouraged to develop their own control system on a PLC architecture. A PLC is a type of digital computer that is generally used in automation for electro-mechanical processes, typically for industrial use. A PLC can be controlled by a simulation program designed on a computer and it is equipped with a set of Digital Inputs (DI), Digital Outputs (DO), Analog Inputs (AI) and Analog Outputs (AO) or Pulse-width modulation (PWM) outputs. This kind of I/O interface is typically conform to strict industrial quality standards with protected inputs (often galvanically separated from the PLC by optocouplers) and outputs. The operating range is commonly at 24V or 4-20mA signal levels. These characteristics are relevant from a didactic point of view, giving the students the opportunity of experience a typical industrial architecture setup. Moreover, a PLC can be logically programmed in different forms, such as a ladder diagram, a structural text and a functional block diagram and stored in memory. These different programming possibilities give students the chance to learn different programming techniques and approaches. A PLC is an example of a hard real-time system since output results must be produced in response to input conditions within a limited time, otherwise an unintended operation will result. These strict requirements force students to design and implement reliable and efficient software.

Control Architecture

The control architecture is shown more in detail in Fig. 3. The *Sykerobot 600-5* manipulator has five axes which are driven by DC motors (24Vdc). Each DC motor is connected to a gear mechanism that provides feedback to two position sensors, a potentiometer and a quadrature pulse transmitter, as shown in Fig. 4 for one of the joint. From the gear box of the DC motor, the output of the motor is delivered via servo spline to the servo arm. The potentiometer's changes in position correspond with the current position of the motor. Therefore, the change in resistance produces an equivalent change in voltage from the potentiometer. The quadrature outputs (A and B signals that are separated by 90 electrical degrees) are feed into suitable decoders/counters that are able to detect direction reversal due to the quadrature feature.

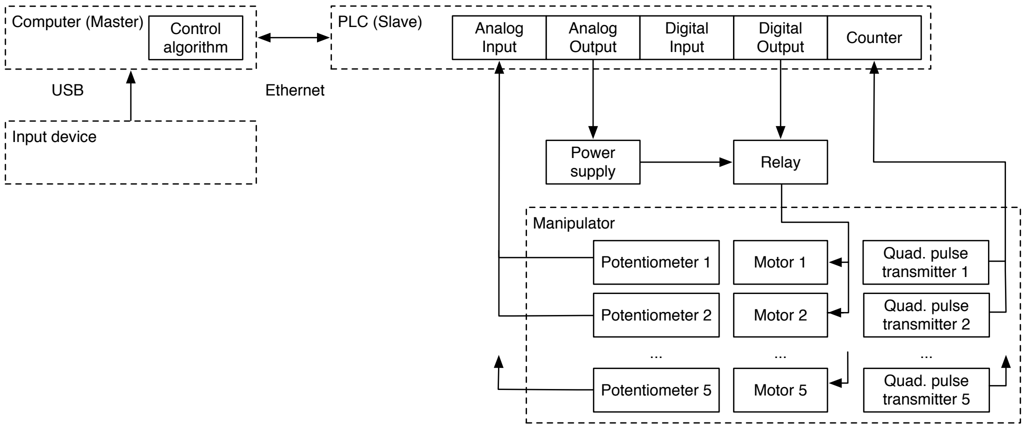

Fig. 3. The proposed control system architecture.

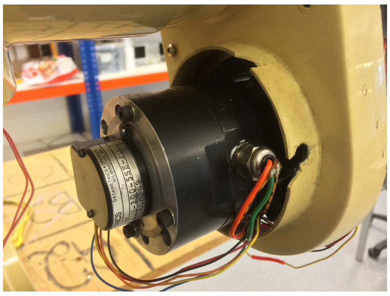

Fig. 4. A detailed photo of the potentiometer and of the quadrature pulse transmitter from one of the manipulator joint.

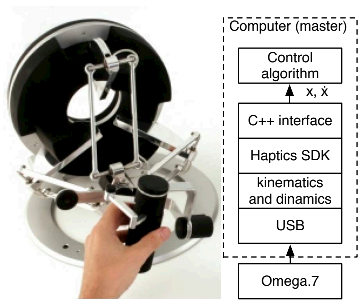

Fig. 5. The *omega.7* haptic device from *Force Dimension* that is used as an input device is shown on the on the left side, while the corresponding data work-flow is outlined on the right side.

Since the control cabinet is no longer available, the motors must be interfaced to some kind of motor controller. In order to avoid buying costly *H bridge* circuits, a programmable power supply board is used. This board can be remotely controlled through a 0-5V signal from the PLC's AO. Besides, the motor revolution direction (clockwise or counterclockwise) is controlled by reversing the polarity with the use of relays.

Input Device

In this case study, a commercial haptic device, the *omega.7* from *Force Dimension*, is used as the input for the system. This device is shown on the left side of Fig. 5 and it is considered state-of-the-art in this field. This choice is justified by the AAUC's goal of providing the students with some of the newest technologies, as well as by the adopted recycling policy. Furthermore, from a pedagogical point of view, the integration of new technologically advanced devices with out-of-date disposed electronics engages students in challenging tasks. The integration of the *omega.7* is realised by using the *Haptics SDK* provided by *Force Dimension*, as shown on the right side of Fig. 5. The position is read by using a C++ interface and used as the input for the control algorithm.

The *omega.7* is a seven DOFs haptic interface with high precision active grasping abilities and orientation sensing. Finely tuned to display perfect gravity compensation, its force-feedback gripper offers extraordinary haptic features, enabling instinctive interaction with complex haptic applications. Since this particular input device presents a higher number of DOFs compared to the controlled robot, the students are challenged to find a mapping approach. A quite interesting solution implemented by the students consists of using the first three DOFs of the *omega.7* to specify the desired position, while the next three DOFs are utilised to set the end-effector orientation. Finally, the seventh DOF is reserved to control a possible tool to be mounted on the manipulator tip.

It should be noted that thanks to the modularity of the proposed system architecture, a different input device can be also used without affecting the effectiveness of the proposed method.

RESULTS

During this learning experience, students have the chance to involve themselves into realistic challenges in the design and implementation of complex systems and to integrate the knowledge and skills gained during their courses. The LBD, PBL, and AL approaches all share a closed loop learning process where the learners get immediate and objective feedback on their progress towards solving the problem at hand. This assimilation process is illustrated in Fig. 6.

Even though our students are undergraduate students, they experience the same benefits that Papert observed in high school students (Papert 1980). He emphasised that learning takes place easily when knowledge fits into the students' learning model: *"Anything is easy if you can assimilate it to your collection of models. If you can't, anything can be painfully difficult"*.

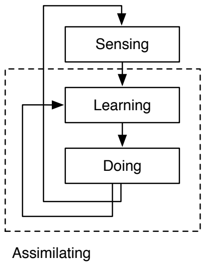

Fig. 6. The effective learning paradigm.

CONCLUSION AND FUTURE WORK

In this work, a combination of the LBD, PBL, and AL approaches is applied to a particular case study: recycling a discarded robotic arm for automation engineering education. According to the feedback received by our students, this experience has shown positive results and improvements on both a learning and a social level. When giving the students the possibility of doing and applying theoretical knowledge on practical experiences, the assimilation process is faster and the social climate of the class improves.

The proposed approach enables students to gain practical knowledge of the integration of different engineering fields, including mechanics, programmable logic controllers, BUS systems, kinematics and control systems. A team learning strategy is proposed and support to hands-on activities in an open-space laboratory is provided. One of the most important learning gains for students consists of getting familiar with different engineering fields by working through a scenario that simulate some challenging industrial tasks and conditions.

According to the author's experience, the involvement of students with triggering and inspiring tasks results in their acquiring new skills and knowledge at higher levels of learning, including analysis, synthesis and evaluation.

As future work, this same learning approach can be applied to new groups of students in order to certify the effectiveness by constantly monitoring them with a set of targeting questions and surveys.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of the students Bjarne Andrè Humlen, Anders Bakken Kobbevik, Simon Langlo, Daniel Nedregård.

REFERENCES

Albanese, M. A. & Mitchell, S. (1993), 'Problem-based learning: A review of literature on its outcomes and implementation issues', *Academic medicine* **68**(1), 52–81.

Bolton, W. (2009), *Programmable logic controllers*, Access Online via Elsevier.

Callaghan, M., Harkin, J., Scibilia, G., Sanfilippo, F., McCusker, K. & Wilson, S. (2008), Experiential based learning in 3d virtual worlds: Visualization and data integration in second life, *in* 'Remote Engineering & Virtual Instrumentation, (REV 2008)', REV.

Chung, C. A. (1998), 'A cost-effective approach for the development of an integrated pc-plc-robot system for industrial engineering education', *IEEE Transactions on Education* **41**(4), 306–310.

Denavit, J. (1955), 'A kinematic notation for lower-pair mechanisms based on matrices.', *Trans. of the ASME. Journal of Applied Mechanics* **22**, 215–221.

Dewey, J. (1997), *How we think*, Courier Dover Publications.

Liu, C., Sanfilippo, F., Zhang, H., Hildre, H. P., Liu, C. & Bi, S. (2012), Locomotion analysis of a modular pentapedal walking robot, *in* 'Proceeding of the European Conference on Modeling and Simulation (ECMS)', pp. 441–447.

Martín, E., Lázaro, C. & Hernan-Losada, I. (2010), Active learning in telecommunication engineering: A case study, *in* 'Education Engineering (EDUCON)', IEEE, pp. 1555–1562.

Modbus, I. (2004), 'Modbus messaging on tcp', *IP Implementation Guide v1. 0a, North Grafton, Massachusetts (www. modbus. org/specs. php)* .

Nguyen, M.-C. & Graefe, V. (2001), Learning by doing-an approach to robotic skill acquisition, *in* 'SICE 2001. Proceedings of the 40th SICE Annual Conference. International Session Papers', IEEE, pp. 226–229.

Papert, S. (1980), *Mindstorms: Children, computers, and powerful ideas*, Basic Books, Inc.

Rekdalsbakken, W. & Sanfilippo, F. (in press), Enhancing undergraduate research and learning methods on real-time processes by cooperating with maritime industries, *in* 'Proceeding of the European Conference on Modeling and Simulation (ECMS 2014)'.

Sarik, J. & Kymissis, I. (2010), Lab kits using the arduino prototyping platform, *in* 'Frontiers in Education Conference (FIE), 2010 IEEE', IEEE, pp. T3C–1.

Zhang, H., Zheng, W., Chen, S., Zhang, J., Wang, W. & Zong, G. (2007), Flexible educational robotic system for a practical course, *in* 'Integration Technology, 2007. ICIT'07. IEEE International Conference on', IEEE, pp. 691–696.

AUTHOR BIOGRAPHIES

FILIPPO SANFILIPPO is a PhD candidate in Engineering Cybernetics at the Norwegian University of Science and Technology, and a research assistant at the Department of Maritime Technology and Operations, Aalesund University College, Norway. He obtained his Master's Degree in Computer Engineering at University of Siena, Italy.
Email: fisa@hials.no

OTTAR L. OSEN received his M.Sc. in Cybernetics in 1992 at the Norwegian University of Science and Technology and holds the position of Assistant Professor at Aalesund University College, Norway. He also holds the position of Head of R&D at ICD Software in Aalesund, Norway
Email: oo@hials.no

SALEH ALALIYAT was born in Jenin, Palestine. He is currently working as a PhD candidate at Aalesund University College, Norway. He received his Masters degree in Media Technology from Gjvik University College in Norway.
Email: saal@hials.no