ETFCam - a Multifunctional Didactic Model for Machine Vision and Automated Visual Inspection

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***Abstract*—This paper presents the development and implementation of a flexible industrial machine model for automated visual inspection, called ETFCam, designed to improve the learning outcomes of electrical engineering students in the field of machine vision and robotics. Unlike prefabricated didactic models, which are typically "closed" systems with a predefined set of experiments, custom didactic systems for teaching and training built from scratch tend to be more flexible and provide a deeper insight in engineering, machine design and planning, while being more cost-effective. The proposed system is based on a 3DOF stepper motor-based manipulator, a DC motor driven conveyor, a pneumatic actuated gripper and a machine vision system. The paper discusses several applications of such a system in an educational environment, with a special focus on machine vision applications. Due to the fact that the system is versatile, open, modular, and easy to upgrade, it has unlimited potential and possibilities for further development. In addition, it provides students with a perfect testbed for learning new engineering skills in many areas such as schematic drawing and understanding, PLC based control, sensing, and machine vision.**

***Keywords*—education; engineering; didactic model; machine vision; automatic control;**

I. Introduction

Training students to become proficient engineers is a very challenging task, as it requires them to acquire and enhance essential skills and knowledge in both theory and practice [1]. Practical skills, in contrast to theoretical ones, typically arise through direct experience while tackling actual problems in real-world settings. To acquire crucial practical knowledge for their future careers, students must face real engineering challenges frequently throughout their education.

A common method for to transferring practical knowledge to students involves utilizing educational models and systems that replicate a real-world object or setup. This helps students to acquire "supervised" industrial experience, e.g. by working on projects during lab hours or on a final thesis. Two types of didactic models are generally used in educational environments:

- prefabricated model e.g. [2–4],
- custom-made models, e.g. [5], [6].

The primary drawback of prefabricated systems lies in their high cost and their lack of flexibility for various projects needing frequent adjustments. Unlike prefabricated models, which are typically standardized to faithfully emulate the industrial setup, in-house developed didactic systems for teaching and training are usually more flexible for different purposes and more cost-effective. In addition, if planned properly by an instructor, students can assist in designing, building, and testing the model, hence they can be involved in the design phase and not only in exploitation.

Numerous important skills are necessary for Electrical Engineering students to acquire to effectively operate in an industrial setting. These include Programmable Logical Controllers - PLCs [7], the integration of machine vision and industrial robots [8], different types of industrial communication protocols [9], SCADA [10], simulations and modeling of an industrial plant [11], among others.

This paper presents a multifunctional didactic tool for machine vision and automatic visual inspection developed on the Department for Automatic control and Electronics, Faculty of Electrical Engineering, University of Sarajevo. The proposed didactic system of an industrial inspection line is built upon a conveyor belt driven by a DC motor, a 3 DOF robot manipulator powered by stepper motors, three different PLCs and two Human Machine Interfaces (HMIs) for controlling the system, several different types of sensors that monitor the operation of the system, and a control cabinet. The machine vision and image processing system is developed on a PC that communicates with the PLCs in real time. The main contribution of this paper is to emphasize the benefits of designing, building, and using such systems in educational environments. The proposed approach:

- allows students to be actively involved in designing, building and upgrading a complex system, that faithfully simulate an industrial process,
- helps students to successfully overcome the gap between theory and practice,
- allows students to learn and successfully apply theoretical knowledge in motion control, electronics and image processing,
- enables both students and lecturers to conduct further research in the real-time image processing and robotic applications.

The paper is organized as follows. The developed didactic system is presented in Section II. Section III discusses the benefits of using the proposed system for educational and research purposes. The conclusion and guidelines for future work are given in the last section.

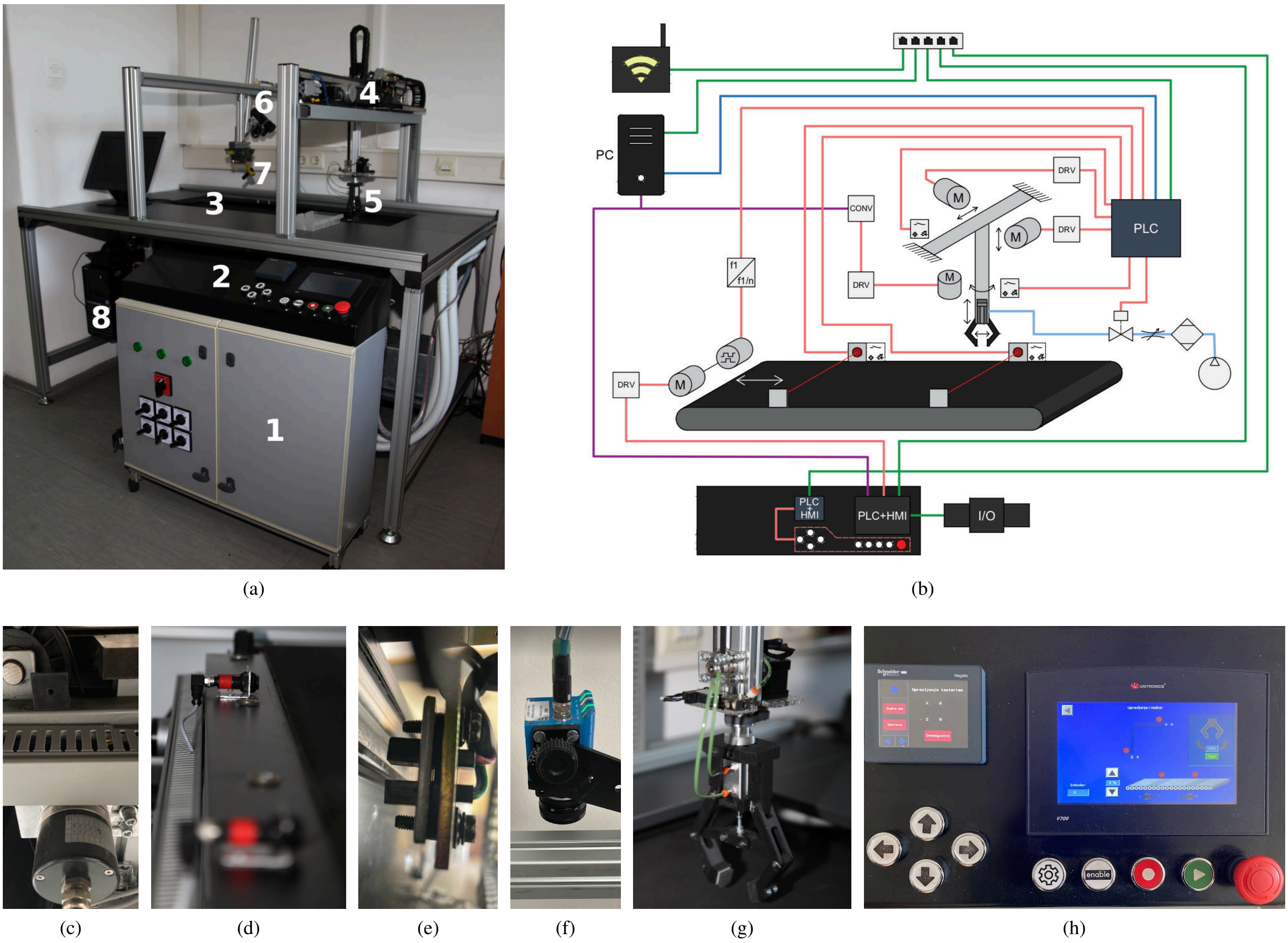

Figure 1. a) ETFCam - actual system - 1-control cabinet, 2-HMI, 3-conveyor, 4-robot manipulator, 5-gripper, 6-camera, 7-laser, 8-PC, b) ETFCam - functional schematic, c) encoder, d) photosensor, e) photopair, f) camera, g) gripper, h) HMI and control interface.

II. ETFCam - Structure and Implementation Details

The complete multi-functional model is presented in Fig. 1a) while its functional schematic is given in Fig. 1b).

Technical specifications and requirements - The proposed system is designed to be completely open-concept, modular, editable, and customizable. It consists of different industrial components to faithfully emulate the industrial environment as much as possible but is not restricted (limited) to only one equipment manufacturer. The machine vision system is designed to be based on open-source software. Despite its cost-effectiveness, its design ensures that it is safe for student use.

System structure - The system components can be separated into the following groups: moving parts (conveyor, robot manipulator, pneumatic system), sensing (pushbuttons, limit switches, photosensors, encoders, industrial cameras), motor drivers, control components (PLCs, PC), communication components, and auxiliary components.

Actuators - Conveyors are the most common means of transport that can be found in an industrial environment; therefore, it was chosen as the main transport mechanism for the proposed educational model. The speed of the DC motor conveyor is monitored using incremental encoder (Fig. 1c)) and controlled using a motor driver and PLC. An in-house designed 3 axes (TTR) gantry robot powered by step motors is chosen as object manipulator. It has two linear axes and one rotational axis (Fig. 1a)). It is equipped with two types of grippers - electromagnetic and pneumatic (Fig. 1g)), and it is capable of picking and placing, pushing, stacking objects. In addition, the model is equipped with a simple pneumatic circuit powered by a lower capacity dry-air compressor sufficient for the actuation of a gripper and other pneumatic cylinders.

Sensing elements - Different types of sensors are integrated in ETFCam. Some of them are photosensors - used for e.g. triggering events on object detection (Fig. 1d)), photopairs - used for homing and calibration (Fig. 1e)), limit switches - used for detecting end positions, pushbuttons - used for manual "jog" operation of the model (Fig. 1h). The model can

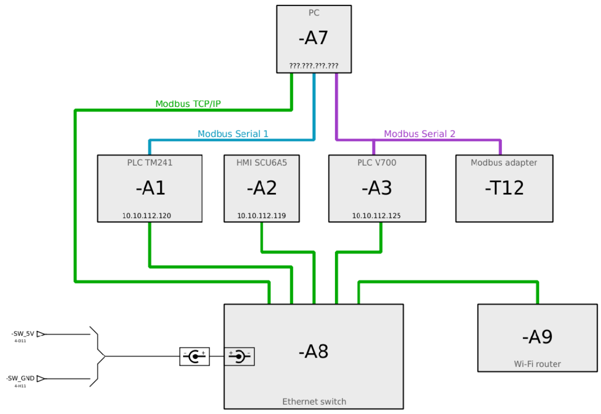

Figure 2. Communication architecture - connection of different devices using MODBUS TCP and RTU/serial master-slave networks

also be equipped with different types of industrial cameras. ETFCam has been integrated with several cameras such as Sony XC-55 (which require a dedicated framegrabber), Basler aca640-750uc, Sick picoCam and Sick Ranger (which use industrial standards - GiGE Ethernet and USB). They provide programmable IO possibilities and have API and interface support for developing custom machine vision solutions.

Drivers - In order to drive the stepper motors, 3 stepper motor drivers Wobit SMC64 are used, excited with Pulse Train Output (PTO) and Direction signals. A dedicated electronic circuit is used as the driver for the DC motor. As part of future work, to closely replicate an industrial solution by employing an AC asynchronous motor with a Variable Frequency Drive to operate the conveyor belt.

Control/processing elements - The system is equipped with three PLCs, Schneider M241 series, Schneider HMI SCU6A5 which is a integrated PLC HMI module with a PLC and Unitronics Vision V700 series with expansion IO modules. Although the use of three distinct PLCs and two HMIs for this technical operation might seem excessive in a genuine industrial setting, their primary function is to instruct students on how to operate and create links between various PLCs from different manufacturers. The PC running Linux and OpenCV/C++ is used as "hardware in the loop (HIL)" which is used to perform image processing and interacts with the actuators and sensors throughout the PLCs.

Communication and auxillary elements - All PLCs, controllers and the PC are connected over the MODBUS, throughout a switch and a RS485 backbone for communication purposes (Fig. 2). The modules may exchange information between each other in different configurations using MODBUS TCP and RTU/serial, which is an open source protocol and it may be easily implemented over RS485 physical interface. Additional parts such as fuses, RCDs, power supply units, auxiliary relays, control cabinets, mechanical construction are integrated in the system.

III. Results, usages and applications

The primary function of the didactic model is to serve as an engineering education testbed that closely replicates the industrial setup. Throughout the design and development process, particular emphasis is placed on enabling students to persistently engage in projects without interfering with earlier activities and hardware configurations. In order to showcase the utility and flexibility of the model, we will list a number of tasks that have been performed by students (under the supervision of professors or technicians) on ETFCam throughout the years:

- Schematic drawing and cabinet planning/wiring,
- PLC programming,
- HMI design and HMI programming,
- Learning methods for software organization and collaboration,
- Planning and implementing communication network architecture and different protocols,
- Learning open-loop and closed-loop motion control (motors and actuators),
- Planning and controlling pneumatic circuits,
- Learning basic skills in mechanical engineering, such as 3D modelling and 3D printing,
- PCB/Electronic design for specific functionalities,
- Machine vision and robot control.

A. *Real-time image processing*

In machine vision and image processing, a significant gap exists between theory and practice. Factors like noise, reflections, camera artifacts, and processing times, often overlooked in theoretical discussions, are inherent in real-world setups. Students can better understand these elements by testing in real-world conditions. ETFCam, designed for industrial visual inspection and machine vision, has been used to implement and test some machine-vision tasks, such as:

- Camera interaction and calibration - software and hardware triggering, camera calibration, different framerate and exposure setups etc.
- Dimensioning of static and moving objects with and without controlled lighting,
- Optical Character recognition,
- Counting objects on static and moving conveyor,
- Object detection, location and classification,
- 3D profiling using laser lines,
- Bottle and cap inspection,
- Quality control etc.

Most of the algorithms were implemented using OpenCV/C++ libraries, and some have been already published (e.g. [12]).

B. *Machine vision based motion control*

The most complex machine vision projects from the engineering point of view include interactions of sensors, actuators/robots, and image processing system. Hence, four most interesting ETFCam projects will be briefly presented.

"Follow me" - a machine vision solution which enables the operator to monitor the operating space of the robot using the

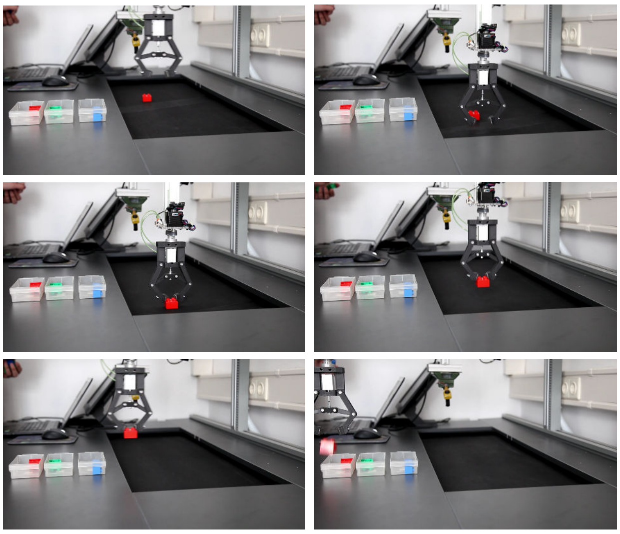

Figure 3. Successive frames during the pick-and-place operation

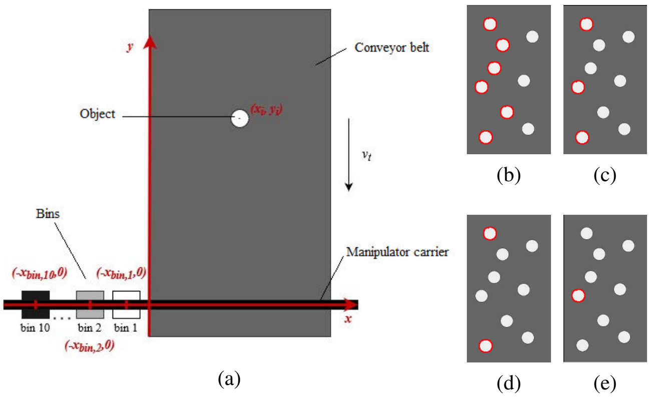

Figure 4. a) Simplified positional diagram of the model (top-down view), b-e) illustration of "optimal strategy picking" algorithm (based on interval scheduling algorithm) in the case of different manipulator to conveyor velocity ratios $r = v_{man}/v_{con}$ and arbitrary object disposition. Picked objects are encircled in red. (The maximum velocity of the manipulator is $v_{man} = 1$ m/s, b) $v_{con} = 0.002$ m/s, c) $v_{con} = 0.05$ m/s, d) $v_{con} = 0.1$ m/s, e) $v_{con} = 0.2$ m/s)

camera, to click anywhere in image space, and the robot then follows and positions itself at the given point.

"Pick and place - static case" - task is to pick a statically positioned object in the field of view of the camera, and place it at a suitable position.

"Pick and place - dynamic case" - task is to pick a moving object on a conveyor (Fig. 3, see video on https://youtu.be/Gm6vMOLmNuw) Unlike the "static case", the position of the object to be picked needs to be determined in advance and synchronized using encoder. The time slot for picking up the object is limited and should be planned accordingly. It requires simultaneous image processing and motion control, implemented using different computer processing threads.

"Optimal picking strategy" - Due to robot speed limits, it is possible that there are more objects on the conveyor than the robot is able to pick up. If the goal is to pick as many objects as possible using given speeds, number of objects, and their positions in a given image frame, different strategies need to be developed for optimal picking (e.g. interval scheduling). Fig. 4 shows one example of a picking scenario based on robot geometry, its initial state, and assumptions that all objects are of equal importance.

IV. Conclusion and Future Work

This article introduces a versatile custom-made educational model of an industrial machine designed for automatic visual inspection, designed for educational purpose of electrical engineering students. The architecture, technical prowess, and implemented projects of the system are presented. As a system developed in-house, mainly for the educational needs of electrical engineering students, it has proved and continues to prove its substantial value for both current students and future engineers. The model integrates theoretical and hands-on aspects of automatic control and machine vision. The system's open design facilitates ongoing enhancements with various hardware, software, tools, and algorithms. The system is also cost-efficient, making it possible to duplicate on a limited budget to enhance the practical comprehension of control and machine vision in the field of engineering.

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