A new generation of collaborative robots for material handling

Ernesto Gambao [1]*, Miguel Hernando [1], and Dragoljub Surdilovic [2]

[1] Centre for Automation and Robotics, UPM-CISC, Madrid, Spain
[2] Fraunhofer Institute for Production Systems and Design Technology, Berlin, Germany
** Corresponding author (ernesto.gambao@upm.es)*

Purpose The handling of material is a high resource consuming task in many different manufacturing industries and especially in the construction sector. Global demand for material-handling products is projected to rise by 7.0 percent annually until 2014 to a total of $119 billion. Typically, work on the construction site, in the materials distribution process or in the construction materials production, includes extensive material handling tasks. Advanced automation and robotics technologies can enhance the productivity of this process, guaranteeing at the same time the highest level of safety for workers. Modular reconfigurable robotic systems are considered as one of the most challenging topics. A worldwide cutting-edge technical solution for material handling, based on the development of a modular intelligent power assists systems (collaborative robots, COBOTS), is presented in this paper. **Method** Conventional manually-guided handling systems lack an intuitive and responsive control and may lead to back discomfort and fatigue. A significant improvement has been achieved by power-assisted systems developed by Stanley Cobotics in the USA, as well by the first cobot prototypes in German industry implemented through cooperation of IPK and Schmidt-Handling GmbH. The proposed material handling approach would constitute a significant breakthrough by bridging the gap between fully automatic and manual technologies. The developed intelligent power systems are capable of working with people also in a direct physical contact, combining human flexibility, intelligence, and skills with the advantage of sophisticated technical systems. Safety issues have been considered to be of paramount importance. **Results & Discussion** A modular flexible collaborative robot prototype has been designed and developed as a demonstration of the proposed new generation of material handling methodology. This technology supposes a break with traditional paradigms regarding flexibility, cost, accessibility and applicability of high-tech handling solutions as well as conventional human-machine interaction. The control system is based on hierarchical order control block architecture. Since a collaborative robot is characterized by real cooperation between human workers and intelligent assist devices, an elaborate safety system has been developed. The prototype can operate in an area of about 4.7x2.4m including travel in Z-direction of about 1.3m. It has five powered axes driven by servo drives. The axes are the X-, Y- and Z-axes, rotation about the Z-axis and pivoting up and down of the end effector. To allow simple and friendly interfacing with the human worker, a sophisticated human machine interface, based on a touch panel, has been developed.

Keywords: *material handling, collaborative robots, modular robots, robots in construction.*

INTRODUCTION

In the manufacturing industries, and especially in the construction industry, a lot of efforts are expended in material handling tasks. This situation has produced a significant increase in the demand of material handling products that allows reducing these efforts, decreasing the consumed time and the costs of this activity. Global demand for material handling products is projected to rise 7.0 percent per year till 2014 to $119 billion[1]. Materials handling products and systems are found in almost every manufacturing and distribution company and for an endless number of goods. If we put our focus in the construction industry, material handling tasks are present in typical works in the construction site, in the materials distribution process, or in the construction materials production.

During many years, material-handling products has been developed using traditional manipulating technologies, trying to reduce the worker efforts in lifting and moving materials. However, conventional manually guided handling systems are in lack of intuitive and responsive control that may cause back discomfort and fatigue. Current industry trends, such as shorter product lifecycles, reduced time-to-market and mass-customization require new paradigms and approaches for handling technology. The growing numbers of product variants and dimensions, as well as smaller lot sizes, have led to increasing demands on flexible material handling equipment and concepts. They must realize high flexibility related to variants, cost-effective adaptability to specific products and processes, and quick in-process reconfiguration and set-ups. In order to master these challenges, innovative approaches and technologies are required. Automation and robotics technologies have been applied in order to contribute to solve these problems.

To tackle the problems on reconfigurability and agility the semi-automatic approach is the best solution, combining flexible automation and human skills. For the manual material handling, various assist devices are available on the market. However, for applications requiring rapid and accurate movements, they are slow, awkward, non-responsive and difficult to be manipulated. A significant improvement has been achieved by power-assist systems developed by Stanley Cobotics in the USA[2], as well as by the first cobot prototypes in Germany industry, implemented through cooperation of Fraunhofer Institute for Production Systems and Design Technology (IPK) and Schmidt-Handling GmbH[3].

In order to reduce the costs and increase the usability, modular reconfigurable robotic systems are considered as one of the most challenging topics to solve material handling problem[4]. A completely new technical solution for material handling, based on the development of a modular intelligent power assists systems (collaborative robots – COBOTS), is presented in this paper. The proposed material handling approach supposes a significant break-through that bridges the gap between full automatic and manual technologies[5]. The developed intelligent power systems are capable of working with human also in a direct physical contact, allowing to combine human flexibility, intelligence and skills with the advantage of sophisticated technical systems. Safety issues have been considered of paramount importance.

A modular flexible collaborative robot prototype (COBOT) has been designed and developed as a demonstration of the proposed new generation of material handling methodology. This technology supposes a break with traditional paradigms regarding flexibility, cost, accessibility and applicability of high-tech handling solutions as well as conventional human-machine interaction. The COBOT prototype has been tested performing the assembly of windscreens in a car assembly line, a typical task in the automotive industry. This demonstration task presents many similarities with typical construction tasks, where it is necessary to move and assembly construction materials.

COLLABORATIVE ROBOT MECHANICAL SYSTEM

The COBOT demonstration system in (Fig. 1) has been developed to meet demands on flexible and advanced integration of the novel cobotic technology in automotive industry assembly lines. This use case allows to demonstrate their capabilities of material handling and precision assembly operations. The demonstrator has been developed as a 5-DOF gantry robot (Fig. 2) with 3 translational and 2 rotational (TTTRR structure) servo controlled axes. An additional passive mechanical rotational axis around the screen vertical axis has been realized. The prototype can operate within an area of about 4.7 m x 2.4 m including a travel in Z-direction of about 1.3 m. It has five powered axes driven by servo drives. The axes are the X-, Y- and Z-axes, rotation about the Z-axis and pivoting up and down of the end effector. The maximum acceleration in X, Y, Z is 1 m/s^2, and the maximum speed in X, Y, Z is 30 m/min.

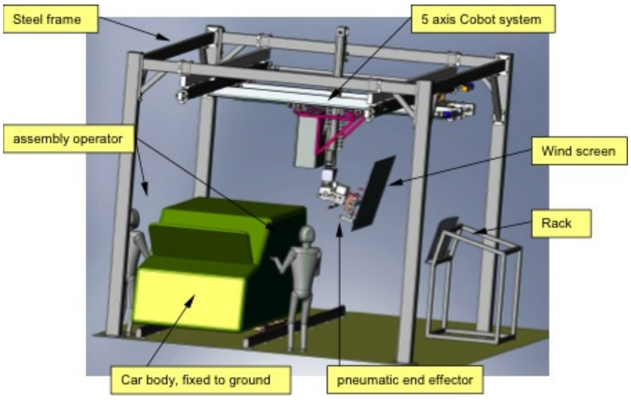

Fig.1. COBOT demonstrator layout

The end effector (Fig. 3) consists of a gripper with four spring loaded vacuum cups. It is designed to handle the front windscreen and the rear window of a passenger car that weights about 20 kg each. The vacuum gripper is designed to pick up the front and the rear window with one set up via suction cups. The spring loading mechanism is mandatory to make up for the different curvatures of the two window types. It also supports the mounting process and allows the Cobot to be less precise. There is an ultrasonic sensor that detects the available window on the rack and thus enables the switching on of the vacuum. The pivot point allows the gripper to rotate a few degrees around a detent, in order to allow a slight manual adjustment of the window during the assembly process and also to take stiffness out of the system.

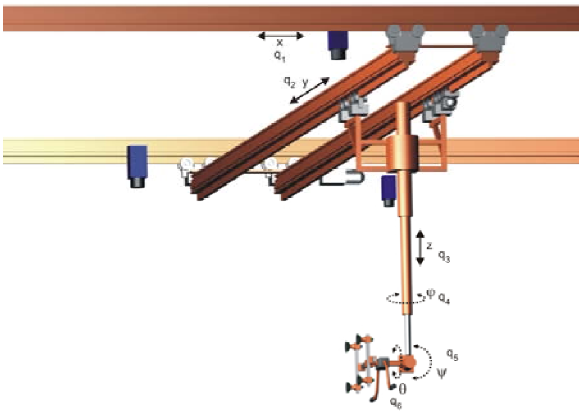

Fig.2. Kinematics of the COBOT

Different from conventional industrial gantry robots, the cobot demonstrator has a relatively lightweight low-cost mechanical structure which absolute precision does not play an essential role by task accomplishment. The critical assembly operations are performed in cooperation with human. Thereby the human operators are responsible to manually guide the cobot to position the windscreen in the car-body frames.

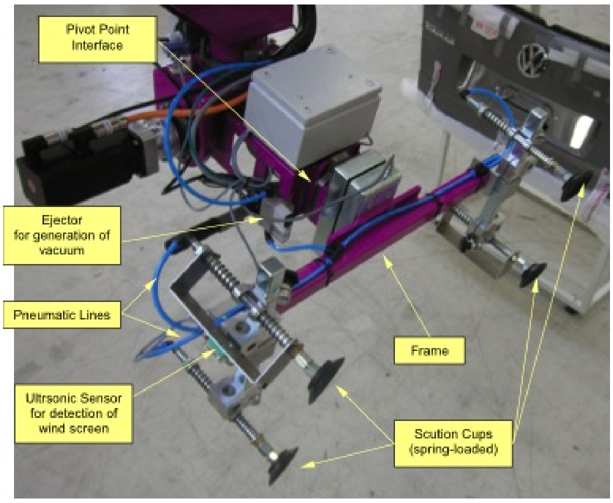

Fig.3. COBOT end effector

The gantry cobot has been designed over a virtual assembly line fixed to the ground. The car bodies (mock-ups) are moving along the virtual assembly lines. The demonstrator includes also a virtual glue station where the cobot should automatically pick-up the screen (using vacuum suction cups) and positions it close to the car-body. Thereby the cobot follows the car-body motion on the line. The system keeps a prescribed distance to the car body until the operators grasp the handling devices (i.e. both hand gripper with sensors) and activate the manual guided assembly phase. After human guided screen assembly the vacuum grippers are released (using switches in the grippers) and the cobot automatically start the retract operation (from the body car). After reaching a start position, the entire cycle is repeated.

For safety reasons the travel speed is limited to 0.25 m/s in interactive (manual) mode and 0.5 m/s in automatic mode. The prototype includes moving indicator lamps and emergency stop buttons.

MECHANICAL AND ELECTRICAL INTERFACES

The mechanical interfaces are the flange for different end effectors and the steel frame. As for the Cobot the flange consists of a simple plate with four tapped holes. This plate is integrated in the housing of the load cell. The steel frame rests on four stands (see picture 5-2) and has a size of 4,5 m x 6 m x 4 m (width x length x height). The steel frame is a free-standing structure, but the feet of the frame could also be screwed to the floor.

The electrical interfaces are:

- Plug for 400 V three-phase current to be turned on and of with a respective switch, mounted on one stand of the steel frame.
- Emergency Stop switch close to operator handle bar
- Additional emergency stop switch(es) at locations to be determined
- Ethernet network connection to attach PC for service of Cobot control

The prototype also includes a pneumatic 6 bar dry air supply for the end effector operation. Figure 4 shows the COBOT prototype working in manual mode.

Fig.4. COBOT operated in manual mode

CONTROL SYSTEM ARCHITECTURE

The cobot control system (CCS) represents a central part of the Cobot prototype (Fig. 5) that integrates all system modules: the cobot mechanical part with digital drives (communication has been realized by EtherCAT), safety controller, assembly planning and programming environment and human-machine interface. The cobot controller provides a sophisticated PC based control system (running under Windows CE and integrated in the Beckhoff TwinCAT real-time environment) providing high level (at action-layer) robot/cobot programming and sensor-based control functions (compliance control, haptic rendering etc.). An assembly task-programming environment supports the task-oriented programming of robot/cobot applications involving off-line simulation tests of programs and system performance. A human-machine interface supports the specific role of the human-operator during commissioning of the system in a work place, including: environment calibration, "manual" i.e. "walk-through" programming (teaching).

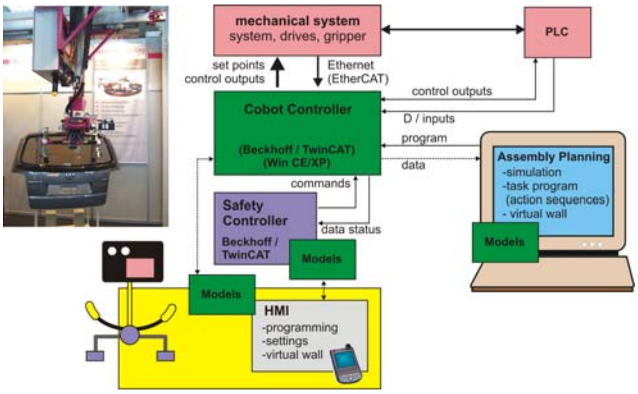

Fig.5. COBOT prototype system architecture

Considering a cage less dual- cobot application (the human is in operational, i.e. achievable workspace,) specific attention in the prototype development is focused on the human and system safety. A special safety controller monitors all system components and human-operator caring for human and environment safety. The safety is not provided as an add-on by the safety controller, rather is an intrinsic part of each module that includes internal safety monitoring and exception handling functions. The safety controller provides additional system safety functions enabling the human operator to come into the robot-workspace in order to realize a task (e.g. interactive windscreen fine-positioning and final assembly). This system integrates additional safeguarding sensors (e.g. laser scanners) and via direct interfaces with the robot controller has the possibility to slow done, hold, stop robot motion or to start a reflective safety action (e.g. stop current motion and starting moving the robot in a contrary direction or to home position).

The prototype CCS system has been developed to meet the following SP1 objectives:

- Integration of intelligent control algorithms supporting semi-automatic and interactive human-robot collaboration, also including direct physical interaction.
- Efficient intuitive programming, including task-oriented, lead-through ("walk-through") teaching programming based on manual-guidance.
- Easy integration in complex assembly demonstration applications in industry (e.g. wind-screens assembly).
- To ensure human and environment safety and protection based on recent robotics and other safety standards and norms

The Cobot functional system architecture, based on a standard hierarchical robot control (ESA Functional reference model – FRM), is presented in figure 6. The main idea of this model is to decompose a complex activity at lower layer components that can be executed by various algorithms and assigned to specific subsystems. This model provides a hierarchical multi-layer control framework. The COBOT functional architecture assumes 4 horizontal layers assembly process control (planning and execution), Task-layer control, Action-layer control, and Servo-layer control. The vertical hierarchy includes the following layers: Forward Control functions – FC involving nominal control functions, Nominal feedback – NNF – caring for external sensor data processing and feedback control loops, and Non-nominal feedback – NNF – performing monitoring function, error detections and exception handling. The safety functions are divided into basic safety function, handling the COBOT device safety issues, and system safety control managing the safety of the entire cobot assembly system.

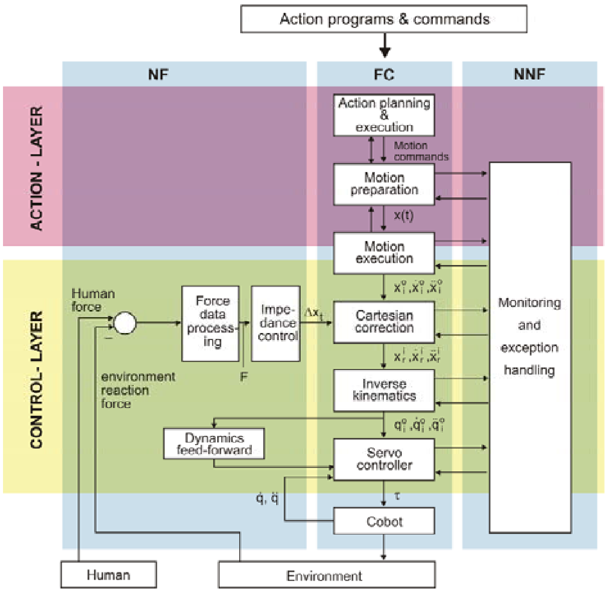

Fig.6. COBOT control functional architecture

ROBOT PROGRAMMING

The programming of the Cobot prototype is based on a high-layer action-oriented programming approach. An action represents lowest level of activity that can be assigned to specific device (e.g. robot/cobot arm, gripper, etc.) and realized based on an appropriate control algorithm. The basic single-arm actions can be split into: non-contact (free-space motion) and contact actions. The specifics actions can be further implemented in the developed programming environment. The basis for the actions programming and environment modeling provides a set of coordinate systems (world-model) and predefined relative poses to these frames.

The assembly tasks represent higher-level activities composed of elemental actions. The goal of task programming is to decompose tasks into elemental actions.

The control architecture of the cobot arm includes common hierarchically ordered control blocks: for the execution of action programs, planning of elemental motion, real time computation of Cartesian set-points, inverse kinematics and servo-local joint control including dynamic feed-forward (compensation of nominal dynamics). A specific key functionality for the controlling human-cobot-environment interaction is position-based compliance, i.e. impedance control. The compliance control allows controlling the physical interaction between the arms and environment, as well as the arms with each other, while maintaining the interaction forces within prescribed limits despite tolerances and inaccuracies. Practically, impedance control provides a basic control approach for all contact (essential and potential) operations. The compliance control will also be used in so-called damping mode for the manual guidance and programming of the robot. By a proper robust synthesis of damping gains sets for the manual guidance in free-space and for the stable transition to the contact, respectively, a good system performance (e.g. fast responsive reaction in the free-space and stable contact transition and guidance in the constraint space) may be achieved.

A special COBOT control functionality represents haptic rendering of virtual walls and controlling the interaction with stiff or flexible virtual obstacles. These functions also utilizes robust robot-environment stable interaction framework. The virtual walls are useful not only to restrict some working area and prevent damages, i.e. injuries, but also to support guidance (e.g. along a virtual wall or cone) to the goal pose.

EXTERNAL SENSORS

The relevant external sensors integrated in the Cobot system are force-torque sensors supporting the control human-robot-environment interaction. Two force-torque sensors are implemented: a 6 DOF compliant sensor for human-robot interaction (manual guiding) integrated in the hand-grasping interface and a 1 DOF contact sensor for the contact detection and monitoring. Figure 7 shows the 6 DOF force-torque sensor in the robot wrist.

Force-torque sensors are essential for the implementation of the above described compliance control method and damping mode that allows manual guidance tanks and direct programming of the robot. Assembly and precision tasks can be accomplished by means of the contact detection provided by the external sensors.

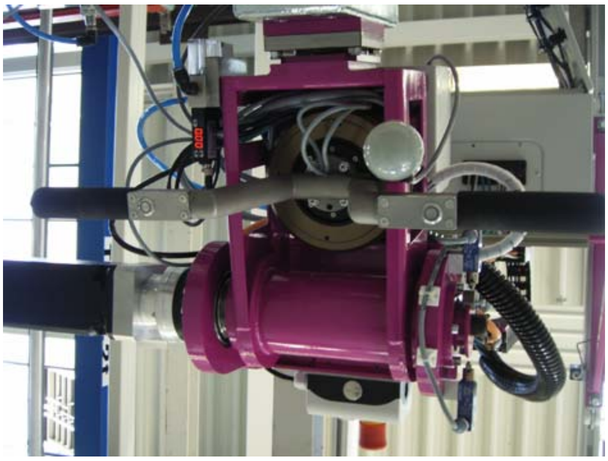

Fig.7. Compliant F/T sensor for human-robot interaction

HUMAN-MACHINE INTERFACE

The main human machine interface has been implemented using a touch panel CP (Fig. 8).

The touch panel PC provides a graphical user interface (GUI) that allows to start the Cobot, to program it, to switch between different modes and to provide user interfaces for different operators who have more or less limited access to the Cobot control.

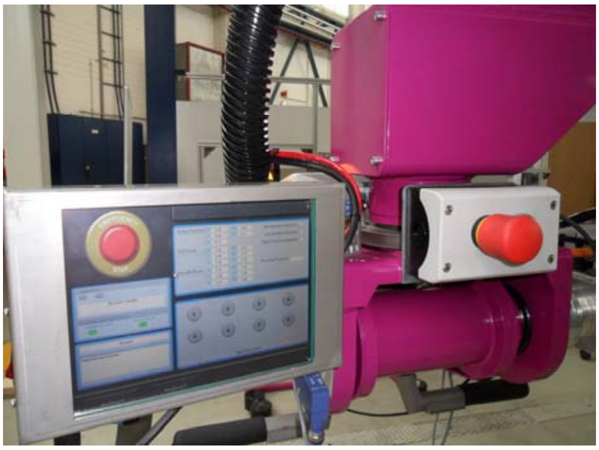

Fig.8. COBOT Graphical User Interface

The touch panel PC also provides feedback to the operator and inform about modes, failures, and states of the Cobot.

In addition there are signal lights on various locations of the Cobot and especially its control box. One light, a flashing light at the control box, signalizes that the Cobot is moving in autonomous mode. Another light signalizes the three different modes: autonomous mode (yellow), manual mode (green), or failure (red).

EVALUATION OF USABILITY

The usability tests were performed using several experienced and non-experienced users. In addition the experience with the numerous users at MOTEK

2009 fair was utilized. The main test was to perform manual guidance using different target behaviors (with and without stiffness) and to perform test tasks consisting of manual guidance, positioning, grasping and finally cooperative assembly of wind screens (using plastic mock-ups).

The test results for the manual guidance and positioning were very good in almost all cases which represents an additional significant improvement in comparison to the state of the art systems and development at the project start. However, the assembly of the screen requires some training and coordination between both operators. In almost 50% of the tests one or both users expressed some difficulties and expressed needs for additional training.

The operability using GUI, handle interfaces or external cobot GUI on a PC was in all cases evaluated as very intuitive and simple. As a critical issue, the position of the user interfaces (handles and mounted GUI) in some cobot poses (e.g. extremely low or high position in z directions, or at maximum horizontal rotation axis stroke) were estimated as not ergonomic. Also the process monitoring by a single-man operation with both hands was evaluated as not enough (due to occlusion by cobot structure) and should be improved in the future products.

COLLABORATIVE ROBOTS VS AUTOMATIC SYSTEMS

Usually completely manual guided robotic systems cannot adequately deal with complex manipulating and/or assembly tasks. Completely automatic robots could be able to perform these tasks with good results, but in many cases with a very high cost. However, collaborative robots present several advantages. In these systems accuracy, flexibility and intelligence is obtained by the combination of the control strategy, technical systems and the presence of the skills of the human operator, instead of using expensive full automatic technologies. Real experiments have shown the benefits of this strategy in the assembly of windscreens in a car assembly line comparing with traditional full automatic solutions.

CONCLUSIONS

Collaborative robots, which combines the benefices of human intelligence and skills with the advantage of sophisticated robotic technical systems, have been demonstrated their advantages when using in material handling tasks. In order to improve their reconfigurability and flexibility the modular approach is the best solution. A completely new modular collaborative robotic concept has been presented in this paper, showing the benefits of using a real prototype in a typical use case for the automotive industry. This methodology can be translated to other manufacturing industries and especially to the construction industry, where material handling and assembly requires considerable efforts.

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