# FourByThree: Imagine humans and robots working hand in hand

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***Abstract*— Since December 2014, FourByThree Project ("Highly customizable robotic solutions for effective and safe human robot collaboration in manufacturing applications") is developing a new generation of modular industrial robotic solutions that are suitable for efficient task execution in collaboration with humans in a safe way and are easy to use and program by the factory worker. This paper summarizes the key technologies that are used to achieve this goal.**

***Keywords—modular, safety, manufacturing, collaboration, usability***

## I. INTRODUCTION

Industrial robots have demonstrated their capacity to answer to the needs of many industrial applications, offering a high degree of dexterity, accuracy and efficiency. Their use is extended to all kinds of applications, but it is in the case of large production batches, repetitive operations or risky or unpleasant working conditions where their introduction has been more significant.

However, when the application requires the collaboration between the robot and the worker, including workspace sharing, it is not feasible to use standard industrial robots due to safety being compromised. Recently, new robotic products have appeared on the marked claiming to be safe when used in the vicinity of humans – examples include the Universal Robots UR3/UR5/UR10 [1] , the Light Weight Robot from KUKA [2], Yumi from ABB [3], the arms from Rethink Robotics[5] or the FRANKA robot [4] presented in the Hannover Messe 2016. These robots offer good solutions for some specific applications where close proximity between humans and robots is a must, allowing to control the force exerted in case of collision, however they lack of flexibility (in terms of possible physical configurations) or are very expensive- some of them are three times more expensive than the counterpart standard ('non safe') version.

Since December 2014, FourByThree Project ("Highly customizable robotic solutions for effective and safe human robot collaboration in manufacturing applications") is developing a new generation of modular industrial robotic solutions that are suitable for efficient task execution in collaboration with humans in a safe way and are easy to use and program by the factory worker. The *FOUR* main characteristics (Modularity, Safety, Usability and Efficiency) of FourByThree are:

*1) Modularity*

FourByThree outcomes are packed as a 'kit' of hardware and software tools for the development of custom robotic solutions. The concept includes fundamental mechanical elements (four different size series-elastic actuators, brackets, flange), the control unit (incorporating advanced techniques for safe HRI) and additional auxiliary hardware/software modules integrated in a ROS based FourByThree control architecture.

*2) Safety*

Safety strategies and low cost mechanisms allowing intrinsically safe behaviour of the robot in the presence of humans were developed. The safety approach is centred around the design of the actuators with the capability to monitor the force and torque in each, providing the opportunity to implement variable stiffness strategies and reactive behaviour in case of contact/collision. The system also includes also space monitoring using a projecting system and a vision system, which provide the information needed to modify the velocity of the robot according to the relative distance with respect to the worker.

*3) Ease of use*

FourByThree offers a set of multimodal interaction mechanisms that facilitate the programming and control of robots, e.g., voice based interaction, manual guidance. These multimodal interaction mechanisms are complemented by human-oriented automatisms ensuring intuitive and safe HRI.

*4) Efficiency*

Robots are intended to help workers in doing a task, to this aim they have to be reliable, maintainable and intrinsically safe. Performance metrics are established for each of application addressed in the project, i.e., assembly, deburring, welding, riveting and machine tending, implemented in four challenging industrial Pilot Studies (Aeronautic, Sheet metal forming, Investment casting and Professional training).

In the following chapters, the key technologies developed in the project are described.

## II. MODULAR DESIGN

### *A. Actuators*

The actuators are complete modules including the motors, gears, sensors, elastic element, and the embedded electronics (together with its software) required to drive and control an elastic single joint. They offer, as well, some of the functionalities needed in the safety strategy, i.e. speed, force and torque monitoring.

**Mechanics.** It was initially decided to build three different actuator sizes (with torques 28 Nm, 50 Nm, and 120 Nm, respectively, at link side) to cover a wide range of possible arm configurations and scenarios. The initial list of requirements contemplated among others: maximum link-side torques of around 28Nm, 50Nm and 120Nm, mechanical deflection of around 5º at the maximum respective torque, compact, modular and lightweight design, link-side speeds of around 15rpm and the use of safety brakes.

Two actuators have been built for the initial prototypes: Type I (28Nm) and Type II (50Nm). The design of the Type III (120Nm) is currently being finished. All actuators are basically based on previous modular actuators designed at DFKI (see example reference in [6]). They combine Robodrive brushless DC motors with Harmonic Drive gears. Additionally, in-house developed motor electronics consisting of four PCBs are embedded within the housing of each actuator. The main difference of these actuators with respect to older versions is that they include an elastic element in series with the motors.

Previous developments of the project CAPIO [7] - which were already using an elastic element - were taken as starting point for building the actuators of Type I (28Nm). The elastic element is a combination of small disc springs placed at both sides of a lever rotating with the motor (see Fig. 1-left). In contrast to the CAPIO actuators, these new actuators include embedded electronics entirely based on FPGA (previously was a hybrid solution using a microcontroller and a FPGA), several mechanical optimizations, and a fourth electronics board acting as 'electronic brake'.

Fig. 1. Actuator Type I: 28Nm.

For the actuators Type II (50Nm), a new spring element based on coil springs has been developed (see Fig. 2-left). The spring coupling has a progressive characteristic: initially it exhibits a linear characteristic until approx. 5º of deflection and, after that, a more abrupt increase of stiffness is introduced. The purpose is to avoid that the spring completely compresses at the maximum torque, but rather it gets stiffer while reaching the maximum torque. The solution has been the introduction of a second harder spring placed inside the 'main' spring.

Fig. 2. Actuator Type II: 50Nm.

**Embedded Electronics.** The basic electronics stack is composed of three PCBs that incorporate all sensors that are required to monitor and control the actuators: motor current sensors are integrated in the low phases of the three-phase H-bridges, and absolute encoders with 19-bit resolution before and after the gear measure the motor position. Additionally, a third absolute encoder is placed after the elastic element to measure the link position. All mentioned sensors as well as current, speed, and position controllers are processed by a Spartan6 FPGA from Xilinx.

Moreover, the actuator electronics has been enhanced in this project with two additional electronic boards: a board for enabling/disabling the mechanical brakes of the Type II actuators (named as 'BrakeBoard') which additionally also monitors the motor phase currents as an additional motor current measurement, and a board for short-circuiting the motor phases of the Type I actuators (the so-called 'electronic brake') to use that effect as electrical brake.

**Low-level Control.** The FPGA-based robot joint controller developed and used previously at DFKI has been extended for the control of the spring deflection. Using a cascaded controller for position, velocity, and motor current, an additional PID control loop regulates the deflection of the spring element of the elastic actuators by either acting on the velocity controller input or by directly acting on the motor current controller input.

Furthermore, the model of the spring deflection and its relative output torque is required for being able to control the actuator torque. The torque-spring deflection is thus modeled by using joint probability densities that are represented by a dynamic Gaussian mixture model (DGMM) [8]. Initial experiments are being carried out to validate the results.

### *B. Robot design*

FourByThree robot system is designed for human-robot collaboration (HRC). Compared to traditional industrial robot systems, the modular robot system can be optimally adapted and used for different tasks and applications. Following this modularity objective, four different robots have been designed to answer the specific requirements of each of the four Pilot studies that are used to validate the concept. They include welding, riveting, handling, machine tending and assembly applications. The robot design provides a modular construction kit developed according to the norms and directives for collaborating robot systems.

Fig. 3. First robot prototype.

The robot construction kit consists of key basic elements: 'base', 'joints', 'link elements' and 'flange'. Thus, depending on the needed applications, different kinds of robot systems can be configured using the construction kit elements. The setup of the robot system is based on virtual modeling of kinematic, derived from the workspace analysis of each application. Using simple calculations, it is possible to determine the custom configuration of the robot system based on the construction kit, for later assembly by system integrators or end users.

### *C. Control Architecture*

A three-layer software architecture is proposed:

- Low level: it includes the drivers and the joint controllers. This level offers an interface with the motors (commands and information retrieval). Lowest control modules, e.g. impedance control and manual guidance, are also included in this level.
- Medium level: It is in charge of controlling the execution of user programs and any other action coming from the higher level.
- High level: It includes system's high level modules, user applications and the Dynamic Task Planner.

ROS is used as core framework for the two higher levels.

### *D. Robot identification and low level control*

Modularity and Compliancy are powerful instruments that will open a wide spectrum of applications for the novel generation of FourByThree robot. However, Modularity and Compliancy are critical aspects in the design of the robot motion and control. Static/dynamic accuracy and repeatability are demanding when standard control strategies are deployed in combination with compliant robots. Step-changes are indeed necessary to address the challenges: (i) preserve the motion smoothness in all the working conditions, (ii) preserve the motion performances compared to standard rigid robots, (iii) auto-tuning of control parameters to overcome changes in working conditions by learning procedures. To face such challenges, the FourByThree will provide a set of innovative motion and control modules.

By considering (i) and (ii) an *elastic-input-output inversion centralized closed-loop controller* (ELIO) will guarantee the maximization of the controllable bandwidth through the integration and the inversion of the completed elasto-dynamic model of the robot [15][16]. The controller will take into account zero-dynamics behavior reducing the control effort. The ambition is to hidden the elasticity of the robot up to 5Hz reaching therefore the typical performance of standard robot of similar payload. However, to overcome the well-known control effort problem with the input-output system inversion, FourByThree robot will be endowed by two motion modules: a high-order motion planner (HELIOS) and an innovative Elasto-Dynamic Identification Tool (EDIT).

HELIOS is a motion planner based on a double concept: it works as motion filter generating a smooth trajectory [13], and the core is based on an optimal constrained predictive control methodology [17], with an optimization window limited to preserve the necessary calculus performance. HELIOS results in a high-versatile motion planner that can be used off-line to plan the smooth trajectory, and on-line as input filter to smooth all the signal sent to the robot control (ELIO).

EDIT is of upmost importance in the FourByThree ecosystem: the tool allows high accuracy in the identification of dynamic properties of the system (friction, masses, inertia, joint stiffness etc.). The tool takes into account the nonlinear estimation of the inertial parameters, and the high-frequency parasitic modes of vibrations. The two effects are decoupled by using a projection method [18]. Furthermore, EDIT integrates in the estimation the minimum analytical representation of the system dynamics [14]. Such feature is fundamental, especially for modular robots, in order to guarantee the maximum accuracy in the parameters estimation, avoiding observability issues of the dynamic system.

Finally, considering (iii), a control procedure with multiple learning levels will be proposed to compensate for friction at joint level (the most relevant problem in robotics applications [19]) and to compensate for robot – environment coupled interaction dynamics [20]. In fact, taking into account industrial interaction robotized tasks, such effects might result in instabilities, force overshoots and task failures. On top of the compliance control, the proposed approach consists in two main control levels: a) iterative friction learning and b) iterative force tracking learning, both relying on the reinforcement learning procedure. While a) allows to locally improve the robot dynamics compensation (needed if working conditions change) iterative and continuously estimating the joints friction parameters, b) allows to improve the interaction task execution, compensating for the elasticity of the interacting environment and avoiding force overshoots, adapting the force tracking control gain and the compliance control damping.

### *E. Variable Stiffness*

The FourByThree robot's impedance control is handled through methods described in §II.D and based on the task at hand and its relevant program. However, it is also necessary to have a higher level mechanism to adjust the robot's impedance based on safety considerations. While basing the robot's impedance solely on the task at hand and the predefined program is fine to achieve the required results for the job, it does not take into consideration anomalies and mistakes in the human or robot's behavior which can lead to safety concerns.

To circumvent this, a higher level stiffness adjustment module is proposed. This module will consider the position and velocity of the robot and the human with respect to each other in order to keep the robot arm's stiffness at a safe level throughout. High velocity and low distance result in a high risk of collision, which means the robot arm's stiffness should be reduced in order to minimize damage.

A fuzzy algorithm approach is considered to implement this. Factors affecting stiffness are distance between the human and the robot, the direction and the velocity of motion. The decision algorithm which is applied through fuzzy logic will map these input values to an appropriate stiffness adjustment output. These input values are obtained through sensors provided as modules in the FourByThree system's architecture. These include RGB-D cameras which allow human and environment monitoring in real-time.

The fuzzy logic mechanism will feed the above sensor data to its fuzzification module. This will use triangular membership functions to map distance and velocity values to fuzzy definitions with their respective μ values representing possibility. The output of the fuzzification module is fed to the inference module. This relies on the product operation to infer the fuzzy stiffness μ values based on the fuzzified input μ values. Thus, the μ values for the fuzzy input are multiplied for distance and velocity to obtain the stiffness μ value. The fuzzy stiffness value itself is obtained through a lookup table that maps different fuzzy distance and velocity values to individual fuzzy stiffness values ranging from 0 to 5. For defuzzification, the center average method is used. Thus, based on the fuzzy stiffness value achieved above and the relevant μ values, the final stiffness value is obtained.

This system allows for a real-time, continuous adjustment of the robot arm's stiffness based on safety concerns. The safe range of the stiffness value is constantly published by this module. The low level impedance controller will consider a stiffness range with which the task at hand can continue. It will then change the stiffness within this range based on the suggestions offered by the high-level stiffness adjustment module. If the suggested change in stiffness falls outside the low-level controller's range for the task, then the circumstances have resulted in the task no longer being safe. In this case, the task will need to stop for the stiffness value to change appropriately.

### *F. Dynamic Task Planning*

The FourByThree control architecture has been endowed wit a dynamic task planner designed and developed to implement continuous task synthesis features, ensure safety critical properties at execution time, and endow the overall system with user modeling abilities for adapting tasks to the different humans at work collaborating with the robot. The integration of plan synthesis and continuous plan execution has been demonstrated both for timeline based planning (e.g., [21]) and PDDL based (e.g., [22]). In scenarios of human robot interaction important problems have been addressed: (a) "human aware" planning has been explored for example in [23], (b) the interaction of background knowledge for robotic planning in rich domain (addressed for example in [24], (c) synthesis of safety critical plans to guarantee against harmful states (relevant in co-presence with humans) is addressed in [25] and [26]).

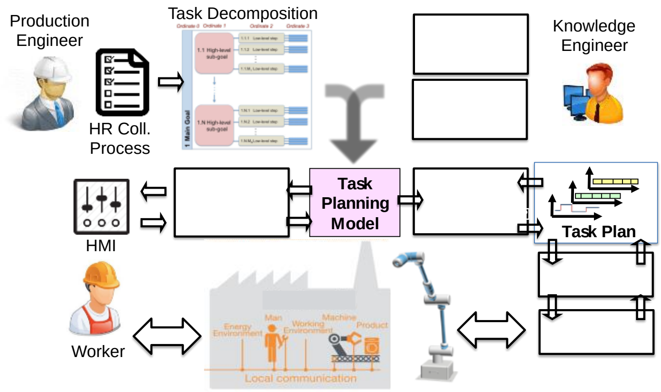


Fig. 4. Dynamic task planning framework.

Within the FourByThree project, a timeline-based planning approach is pursued relying on the APSI-TRF [27], developed for the European Space Agency and exploited in several missions. Then, the envisaged planning framework is to deploy a continuous task planning and adaptation system with humans in the loop. The overall framework is depicted in Fig. 4. A Production Engineer is in charge of defining the Human-Robot collaborative (HRC) production process characterizing each task according to specific HRC settings (i.e., interaction modalities). Then, a Knowledge Engineer is to encode such information in a task planning model following a hierarchical decomposition and leveraging the features provided by a Knowledge Engineering Environment for planning with timelines [28], that integrates *classical* knowledge engineering features with Verification and Validation (V&V) formal techniques to perform domain model validation, planner validation, plan verification, etc. The integration of Planning and technology with V&V techniques is key to synthesize a safety critical controller for the robot. The Task Planning Model can be, then, adapted also according to the preferences of the Human Worker that is supposed to interact with the robot during the production process. A FourByThree Task Planner then generates a temporally flexible task plan to be dispatched to the robot through an Executive System (integrated in the general ROS-based architecture). The dispatched tasks are then to be actually executed on the robot activating the proper control of motion actions and motors activation signals. During the production process, the Executive System is also in charge of monitoring the plan execution and, in case of need (e.g., a specific command issued by the human worker), asks the task planner to dynamically face modifications of the production environment. It is worth underscoring that the task planning other modules are intended to be tightly coupled as motion planning modules are to provide temporal bounds for robot movements while safety modules such as, for instance, variable stiffness module, will leverage the outcome of the dynamic task planning system to better tailoring robot settings while interacting with the human worker.

## III. SAFETY

The safety strategy in FourByThree is based on five pillars:

- The actuators. The design allows measuring the force and torque values using two different physical principles, resulting in a safe approach.
- The robot design, emphasizing the elimination of sharp edges, reduction of the risk of trapping, etc.
- The external monitoring system. It consists of a projection system and a vision system, allowing to monitor the space around the robot to detect any possible violation by the worker.
- Adjustable stiffness control
- The control architecture.

The proper use of those features make it possible to satisfy the operating conditions established in ISO10218 parts 1 and 2, and ISO/TS15066, once the mandatory Risk Assessment has been done.

### *A. Architecture*

The Safety strategy in 4x3 is outlined in Fig. 5.

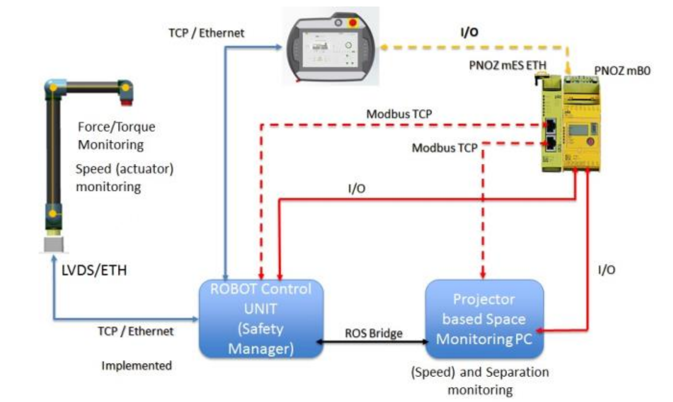


Fig. 5. Safety architecture.

In brief, the FourByThree safety strategy allows (1) defining a protective area around the robot for co-existence and interference situations (i.e., when the human moves through the robot workspace but does not interact directly with the robot or when the human reaches into the robot working area or obstruct the robot workspace in a non-planned task).

The projecting system is in charge of monitoring the robot workspace and triggering the safety signal when there is a violation in the area; (2) for co-operation activities (i.e., when the human has to interact with the robot in a productive way) the system's capability to monitor and limiting the force and torque is used to guarantee the safety.

The safety strategy and the different components are analyzed in collaboration with an external certification body and the certification roadmap will be established by the end of the project.

### *B. Projection based space monitoring*

The projection-based monitoring system is responsible for ensuring human's safety in applications that will not allow a contact between human and robot. This will be the case for instance if the robot moves with high speed, uses dangerous tools for grasping or handles risky workpieces. For monitoring such human-robot cooperation scenarios the Fraunhofer IFF developed an innovative sensor system that is based on projector and camera techniques [9][10]. The sensor system is capable of establishing safety spaces of arbitrary shapes by projecting light from the projector directly onto the environment. Violations of these safety spaces caused by disruptions to the emitted light are robustly detected by surrounding cameras. By incorporating the current joint positions and velocities of the robot, the safety spaces can be dynamically adapted to enclose the robot minimally at any point of time (see Fig. 6).

As there is no need for a complex computation of three-dimensional data of the environment, the implemented algorithms for image processing and collision detection lead to minimal reaction times of the system. Furthermore, the robustness and availability of the system is enhanced through synchronization of projectors and cameras. Here, the cameras are adapted to the frequency of the light emitted from the projector, reducing the influence of environmental light conditions on the collision detection process.

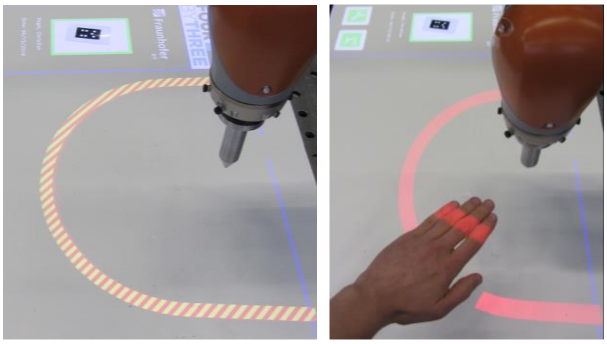

Fig. 6. Dynamically established safety space without safety violation (left) and with safety violation (right).

In "FourByThree" this technology is deployed for applications in real industrial environments. To meet the requirements of various industrial conditions the projection-based monitoring system has been adapted according availability, safety and modularity. Here, single modular projection units have been developed that provide higher flexibility and customizability. Each unit comprises one projector and two cameras that can be adjusted individually. By configuring several units to work together, it will even be possible to operate in difficult environmental conditions with low ceilings or large monitoring areas.

Besides technical improvements that include the enhancement of response time, detection capabilities and robustness, Fraunhofer IFF is working on the evaluation of the sensor system according a future safety certification.

## IV. INTERACTION

Natural communication between humans and robots can happen through several channels, the main of which are voice and gestures. In this multimodal scenario, the information can be complementary between channels, but also redundant. However, redundancy can be beneficial [11] in real industrial scenarios where noise and low lighting conditions are usual environmental challenges that make it difficult for voice and visual signals to be captured with clarity.

FourByThree proposes a semantic approach that supports multimodal interaction between humans and industrial robots in real industrial settings.

### *A. Voice and gesture based interaction*

The approach aims at creating a safe human-robot collaborative environment in which interactions between both actors happen in a natural way (understanding by 'natural' the communication based on voice and gestures). We propose a semantic multimodal interpreter prototype that is able to process voice and gesture-based natural requests from a person, and combine both inputs to generate an understand-able and reliable command for industrial robots, enhancing safe collaboration. For such a semantic interpretation, we have developed four main modules, as shown in Fig. 7: a Knowledge-Manager module that describes and manages the environment and the actions that are feasible for robots in a given environment, using semantic representation technologies; a Voice Interpreter module that given a voice request, it extracts the key elements on the text and translates them into a robot-understandable representation, combining NLP and semantic technologies; a Gesture Interpretation module mainly for resolving pointing issues and some simple orders like stopping an activity; and a Fusion Engine for combining the output of both text and gesture modules and construct a complete and reliable order for the robot.

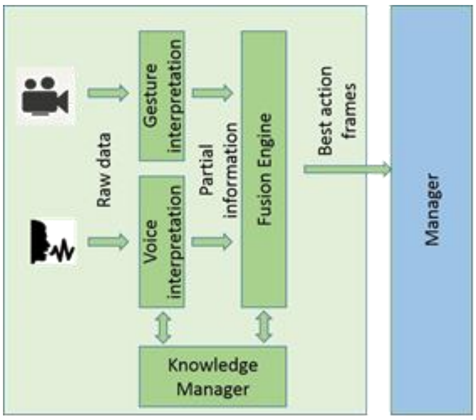


Fig. 7. Multimodal semantic approach architecture

These main modules are described in detail in the following subsections.

#### *1) Knowledge Manager*

The knowledge manager comprises ontologies that model environmental information of the robot itself, including its own capabilities. In addition, the knowledge manager allows modeling the relationships between the concepts. These relationships are implicit rules that can be exploited by reasoners in order to infer new information from the ontology. As a result, reasoners can work as rule engines in which human knowledge can be represented as rules or relations.

#### *2) Voice Interpreter*

Given as input a human verbal request, the purpose of this module is to understand exactly what the person wants and if it is feasible to generate the necessary information for the robot. The first step concerns to speech recognition. The second step is based on superficial information, in the sense that it does not take into account the meaning of words in the context. Its only purpose is to extract the key elements from the given order.

The last step attempts to identify the action that is asked for, considering the key elements in the given context.

The module output consists of frames, one for each potential task candidate, including information denoting gestures, if any exists.

#### *3) Gesture Interpretation*

Two kinds of gestures are addressed within the FourByThree project: pointing gestures and gestures for simple commands such as stop/start. In the case of pointing gestures, they are recognized by means of point-cloud processing. In this context, the system must be able to not only recognize the pointing gesture, but also deliver within a certain period time how many different pointing gestures have occurred and which ones those are, in terms of x, y and z coordinates.

The initial setup consists of the collaborative robot and a sensor capable of providing dense point clouds, such as the ASUS Xtion sensor, the Microsoft Kinect sensor, or the industrial-grade Ensenso system by IDS. The sensor is placed above the human operator and orientated towards the working area of the robot, so that the point cloud obtained resembles what the human operator in perceiving in the working environment.

#### *4) Fusion Engine*

The fusion engine aims to merge both the text and the gesture outputs in order to deliver the most accurate request to send to the executive manager. The engine considers different situations regarding the complementary and/or contradictory levels of both sources.

As a first approach, it has been decided the text interpreter output to prevail over the gesture information. When no contradiction exists between both sources, the gesture information is used either to confirm the text interpretation (redundant information), or to complete it (complementary information).

### *B. Projection based interaction*

Besides the safety aspect of the projection-based monitoring system the technology provides even interaction and visualization capabilities. Here, the system can visualize relevant information to support the user at work but it also allows the user to offer input and information back to the robotic system. This means that the projection system is capable of providing buttons or simple menus that can be used to control the robot, task or process. The shape of these interaction areas and the reaction upon triggering can be configured individually.

At present, two interactive buttons that control the application's workflow have been implemented. A screenshot of these buttons is depicted in Fig. 8. The first one activates the manual task that enables the workpiece detection process and visualizes some additional task-related information. The second button activates the robot task. Thus, the safety space monitoring is enabled and the robot starts its motion and processes the workpiece autonomously.

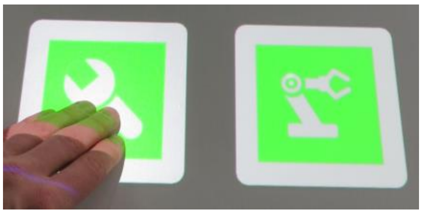

Fig. 8. Interactive buttons control task and robot.

In addition to the interaction possibility, the system performs an access control that offers different interaction buttons regarding the access rights of the user. For this, we implemented an identification area that detects the user's card and processes the user's rights accordingly (see Fig. 9).

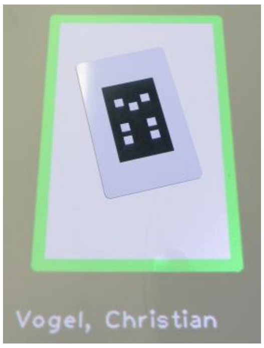


Fig. 9. User identification area with card and identified user.

## V. PROGRAMMING

Industrial robot manufacturers offer their own proprietary programming language that allow typical robot control of movements and I/O management. Most of them offer software packages for the application of domain-specific tasks (e.g., welding, gluing, handling, machining) that contain a set of additional instructions that can be used to program specific tasks. It is becoming very common to offer the possibility of using general purpose languages, such as C, C# or Java to customize and develop applications by end-users. This is the case with KUKA that provides the Sunrise API in its Sunrise Controller in JAVA [12] that, unfortunately, demands high programming skills.

In 4x3, the programing approach allows using both programing by demonstration and standard textual programing.

### A. *Standard programming*

As there is not any widely accepted robot programming language, FourByThree proposes a simple to use language that allows programmers accessing those functionalities.

This standard textual programming includes:

- Open language definition. It has some commonalities with languages used by industrial robots has been defined. It includes movement commands, mathematical operators, I/O instructions, flow control primitives, logical operators, etc.
- Easy to use editor, including a syntactic analyser. The lexical analysis is the process of converting a sequence of characters into a sequence of tokens, i.e. meaningful character strings. This process is generally combined with a syntactic analysis which takes a list of tokens and analyses them conforming to the rules of a formal grammar. A program or function that performs lexical analysis is called scanner, lexer or tokenizer, and the software component that takes the list of tokens and checks for the syntax correctness is called parser.
- Program executor. A component that interprets the content of the program translates it into robot understandable instructions and sequences them.

Scanner and parser functionalities will be implemented using existing tools, Flex and Bison

### B. *Programming by demonstration*

The FourByThree robot is programmable through its proprietary programming framework and compiler as described in §V.A. However, to create an easier interface for workers with no programming experience, a learning module is also considered. This module will enable the worker to program the robot through manual guidance and gesture/voice recognition. Additionally, the module allows the robot's behavior to be tailored to the worker by observing the worker's real-time kinematic behavior and focusing on ergonomics. Thus, a task is divided into coarse and fine movements of the robot, with the coarse movements being 'taught' through manual guidance and the finer movements which are dependent and specific to each worker 'learnt' by observing that particular worker's behavior.

Comfort and ergonomics are familiar terms with typically subjective definitions. Each person has their own thoughts on what is comfort and ergonomics to them, making these parameters hard to assess and compare objectively. Work related musculoskeletal disorders (WMSDs) are the result of issues in these same parameters in the workplace left unnoticed and unattended. There are methods and techniques proposed and currently in use for ergonomics assessments. These range from subjective questionnaires to observation-based measurement and scoring of joint angles involved in a posture and task, and are used regularly in clinical and industrial environments alike and are popular due to their ease of use and lack of a requirement for specific expertise. However, this simplicity has the downside of lack of objectivity and/or thoroughness. A more thorough and objective understanding of comfort and ergonomics can be achieved by relying on sensed data from a human rather than their subjective opinion. These can provide precious information about human behavior and allow assessment of different activities in terms of health and comfort. Furthermore, a real-time objective assessment of comfort will allow for better interaction between robots and humans.

The Rapid Upper Limb Assessment (RULA) method assigns scores to each part of the upper body based on the joint angles associated with it. These scores are then combined together using a look-up table in order to reach one final score, with higher numbers meaning a less ergonomic state. Using orientation sensors consisting of accelerometers and gyroscopes, or RGB-D camera systems, it is possible to obtain real-time values for the worker's joint angles. These joint angles can then be used to reach a real-time ergonomics score based on RULA. This score will then be the basis for the robot's reactive behavior. A high number indicating ergonomics risk will prompt the robot to move into a position that will affect the worker's posture positively, by forcing him/her to move to a more ergonomic state. This is implemented by identifying the different ergonomics states for the worker and using them to create a rewards function for the robot's learning module which will enable it to respond accordingly.

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