A human-driven control architecture for promoting good mental health in collaborative robot scenarios*

Matteo Lavit Nicora[1], Elisabeth André[2], Daniel Berkmans[3], Claudia Carissoli[4], Tiziana D'Orazio[5], Antonella Delle Fave[4], Patrick Gebhard[6], Roberto Marani[5], Robert Mihai Mira[1], Luca Negri[4], Fabrizio Nunnari[6], Alberto Peña Fernandez[7], Alessandro Scano[1], Gianluigi Reni[8], Matteo Malosio[1]

Abstract— **This paper introduces the control architecture of a platform aimed at promoting good mental health for workers interacting with collaborative robots (cobots). The platform aim is to render industrial production cells capable of automatically adapting their behavior in order to improve the operator's quality of experience and level of engagement and to minimize his/her psychological strain. In order to achieve such a goal, an extremely rich and complex framework is required. Starting from the identification of the parameters that could influence the collaboration experience, the envisioned human-driven control structure is presented together with a detailed description of the components required to implement such an automated system. Future works will include proper tuning of control parameters with dedicated experimental sessions, together with the definition of organizational and technical guidelines for the design of a mental-health-friendly cobot-based manufacturing workplace.**

I. INTRODUCTION

The constantly growing concept of Industry 4.0 is leading to completely new workspaces where automation machines cooperate with humans. However, the quality of experience and level of engagement of workers interacting with robots have become an active research topic only recently and still represent a largely unexplored domain. So far, industrial cobots have been primarily studied and designed addressing aspects related to the physical safety of the worker, targeting optimal productivity performance by reducing uncertainty and instability in their cooperation with humans. While these topics still remain of great interest, new research branches must arise in order to explore the role that cobots could have in reducing the workers' psychological strain. The challenge lies in the fact that, differently from applications such as social robotics, the interaction between a human worker and a robot collaborator in an industrial scenario is bound to the specific task and production requirements. However, cobots have evolved to a point where many operations could be performed both by the manipulator and the worker, meaning that a certain degree of freedom in the assignment of subtasks between the two collaborators is possible. Moreover, a series of parameters characterizing human-robot collaboration, also identified in previous works, can be tailored with the aim of optimizing the worker's experience. It is clear that, in order to achieve such a goal, a multidisciplinary approach and a wide partnership contributing with several different fields of expertise are of utmost importance. In this regard, the MindBot project, funded by Horizon2020, has been launched with the aim of defining organizational and technical guidelines for the design of a "mental-health-friendly" cobot-based manufacturing workplace. The first step in this direction is the definition of a setup that enables constant monitoring of the worker's psychological strain and adaption of the behavior of the production cell. This study represents the starting point for this complex automation process, since it aims at defining a suitable architecture able to realize a human-driven control logic promoting good mental health for workers interacting with cobots.

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[1]Matteo Lavit Nicora, Robert Mihai Mira, Alessandro Scano and Matteo Malosio are with National Research Council of Italy, Institute of Intelligent Industrial Technologies and Systems for Advanced Manufacturing, Lecco, Italy. matteo.lavit@stiima.cnr.it

[2]Elisabeth André is with Human-Centered Artificial Intelligence, Institute for Informatics, Universität Augsburg, D-86159 Augsburg, Germany.

[3]Daniel Berkmans is with Department of Biosystems, Animal and Human Health engineering Division, Measure, model and manage Bioresponses (M3-BIORES), KU Leuven, 3001 Heverlee, Belgium.

[4]Claudia Carissoli, Antonella Delle Fave and Luca Negri are with Department of Pathophyisiology and Transplantation, University of Milano, Italy.

[5]Tiziana D'Orazio and Roberto Marani are with National Research Council of Italy, Institute of Intelligent Industrial Technologies and Systems for Advanced Manufacturing, Bari, Italy.

[6]Patrick Gebhard and Fabrizio Nunnari are with German Research Center for Artificial Intelligence, Saarbrücken, Germany.

[7]Alberto Peña Fernandez is with BioRICS n.v., 3001 Heverlee, Belgium.

[8]Gianluigi Reni is with Scientific Institute, IRCCS E. Medea, Bosisio Parini, Lecco, Italy.

II. STATE OF THE ART

Very little material is available when attempting to define cobots' design guidelines and control methods aimed at optimizing the psychological aspects of human-robot collaboration. Nevertheless, some works can be taken into consideration to define the parameters that can influence the operator's experience when interacting with a cobot. In [1] distance from the operator and approaching speed are the main parameters considered for their effect on psychological strain. Results show that as distance increases and speed decreases, the measured level of stress is reduced. Moreover, in [2] and [3], different robot trajectories are tested in terms of how they are perceived by the operator, with promising results regarding the employment of trajectories inspired by human-human interactions. The influence of

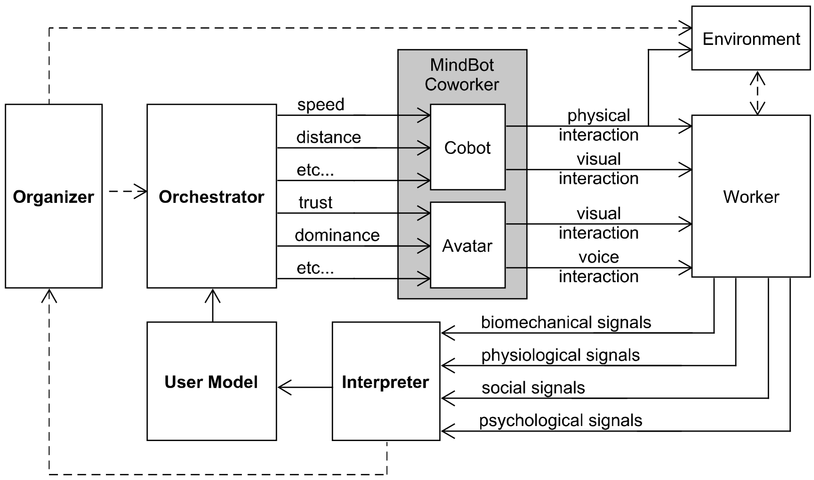

Fig. 1. Human-in-the-loop MindBot control structure

robot appearance and accuracy on the collaborative task was also investigated in [4] and [5]. In general, appearance does not seem to affect the level of trust while a faulty robot is always perceived as less trustworthy.

In [6] and [7], it is shown that information supplied to the operator during the execution of the task can yield higher performances, but the amount of data and the form of communication may have a negative effect on mental health and must be properly selected. From a conceptual point of view, a virtual avatar could act as mediator between the human and the cobot and, as found by [8], the subjective impression could be tailored on the basis of two orthogonal traits: dominance and trustworthiness.

An additional feature of human-cobot collaboration that requires deeper investigation is the experience reported by workers during interactive tasks. In particular, it is important to assess repeatedly and in real time the participants' perception of both the challenges characterising collaborative tasks with the cobot and their own abilities and skills in facing them. As highlighted by research on stress, the balance or imbalance between these two dimensions represents a key factor influencing individuals' quality of experience [9]. In this regard, a vast literature highlighted that the combined perception of high environmental challenges and personal skills adequate to face them fosters the onset of optimal experience, or flow [10], a positive and rewarding state of consciousness characterised by deep concentration, absorption, enjoyment, control of the situation, clear-cut feedback on the ongoing performance, clear goals, and intrinsic reward. Optimal experience can be associated with most daily activities, including work [11] [12], provided that the ongoing task is challenging enough to require concentration, engagement, and mobilization of personal skills and resources. Instead, when perceived challenges are too low, individuals report experiences of boredom or apathy while, when they are too high, an experience of anxiety arises [13].

Starting from these considerations, the aim of this paper is to present a human-driven control architecture able to adapt the human-robot collaboration in a productive workcell to the operator's ongoing quality of experience.

III. CONTROL ARCHITECTURE

The envisioned human-driven control architecture is reported in Fig. 1. As depicted, a series of fundamental blocks are interconnected by solid arrows, representing either the stream of measurable/controllable parameters or a specific type of interaction. The collection of these elements allows for the definition of a closed control loop, running along with the execution of the task.

The first goal is to offer the Worker an experience characterized by social and empathic aspects, even in an industrial scenario. To achieve this goal, the robotic platform includes both a collaborative robot arm, and an interactive virtual Avatar. This additional feature allows to enrich the interaction between the Worker and Cobot, adding gaze, gestures, and talk capabilities to the platform, with physical, visual and voice interaction modes. The system is aimed at achieving high-levels of integration between the Cobot and the Avatar, so that the latter can be considered the representation of the robot in humanoid form. In these terms, the Worker can be said to interact with a unique entity, called MindBot Coworker, represented by the merge of the Cobot and the Avatar.

For this purpose, the behaviors of the Cobot and of the Avatar are coordinated by the Orchestrator module. This module has knowledge of the task to be carried out and of the organization of subtasks between the Worker and the MindBot Coworker. It is also in charge of dispatching information to control the Cobot and the Avatar coherently and consistently. In doing that, the resulting behavior of the MindBot Coworker is tailored on the Worker's mental state in order to minimize negative experiences, such as psychological strain or boredom. The main parameters available for adaption are the ones identified on the basis of previous experimental results, highlighted in Section II: amount of information provided, trustworthiness and dominance for the Avatar and movement speed and acceleration, average distance kept from the operator and more for the Cobot.

The current Worker's mental state is inferred by the User Model block. This second component allows cognitive modeling about affective states of the Worker and regulation strategies, by processing stressors connected to mental focus or stress data. In order to do that, a wide set of heterogeneous information is required, spanning from physical and mental energy to psychological and social data. For this purpose, raw data is collected by sensors and questionnaires and then processed and elaborated by the Interpreter module. In particular, four fundamental signals, aiming to provide a comprehensive representation of the Worker, are used:

- biomechanical signals, to evaluate the physical stress and fatigue of the operator;
- physiological signals, to estimate the mental energy used to perform a task;
- social signals, to estimate the affective state of the user while performing a task;
- psychological information, to infer the quality of experience perceived by the operator.

After the interpretation phase, the list of information fed to the User Model block includes but is not limited to: joint power, physical energy expenditure and fatigue, mental energy use and recovery, level of focus, level of stress, level of boredom, quality of experience and level of engagement of the operator.

Referring to Fig. 1, a second outer loop is represented using dashed arrows. This feature is only briefly introduced here since it represents a core goal of the MindBot project, but is outside the scope of this study. As stated in Section I, a certain degree of freedom in the assignment of subtasks between the cobot and the worker is possible and may represent a great opportunity to further improve the adaptation of the manufacturing cell. The mentioned outer loop is envisioned to serve exactly this purpose. The Organizer block is representative of the role of the researcher that, analyzing all the data logged during the collaboration, proposes a reorganization of the task based on the balance between production requirements and Worker's experience. Moreover, as represented in the diagram, the Organizer is in charge of defining possible changes in the workspace environment. This aspect is particularly important when considering operators diagnosed with autism spectrum disorder (ASD), which will represent a central research topic for the MindBot project in the long-term.

IV. COMPONENTS DESCRIPTION

After introducing the general structure of the control architecture, a detailed description of the hardware and software components needed and identified to achieve the desired functionalities is presented hereafter. Note that, in order to simplify the communication among some of the modules, the authors chose to exploit the functionalities of ROS Noetic Ninjemys [14], a state-of-the-art platform for robotic research.

A. Interpreter

Mental Energy Interpreter - While the worker is interacting with the MindBot Coworker, his/her physiological responses (heart rate, bpm) and movement (steps/min) are monitored by means of wearables, specifically FitBit activity trackers with heart rate capabilities (FitBit Inspire HR, FitBit Inc.). Using these physiological variables as input for the BioRICS' Mindstretch application [15], shown in Fig. 2, it is possible to determine the metabolic energy use and/or recovery for mental tasks exhibited by the workers in real-time while working in the production cell.

Fig. 2. The FitBit tracker (a), the mental energy use and recovery throughout the day (b) and the real-time stress level against the focus zone to determine deviations from optimal status/performance (c).

Mental energy use and recovery is a metric, expressed in the Mindstretch app as a percentage, which relates the mental energy wielded while performing a cognitive task to the mental energy baseline level defined for that individual.. If the cognitive task is demanding, Mindstretch monitors the mental energy used by the individual to perform it. When there is no mental effort required to perform such task, Mindstretch monitors the mental energy recovery induced by that task [16] [17]. The worker needs to wear continuously (day and night) the FitBit, on average, for 3 days prior to ensure that the Mindstretch algorithm is fully adapted to the individual worker. Combining the mental energy monitored by Mindstretch, together with a performance metric, defined according to the specific task, allows defining the focus or Eustress zone of the worker while performing such a task [18]. This mental focus zone is defined as the zone of mental energy use exhibited by the worker when performing most efficiently the task [19]. This focus zone is individually different per worker and will vary within the same day for the same worker. Deviations of the mental energy exhibited by the worker from this estimated focus zone might be used as an indication of distress or distraction, making the worker go out of focus from the task and, thus, inducing a drop in attention and performance [20].

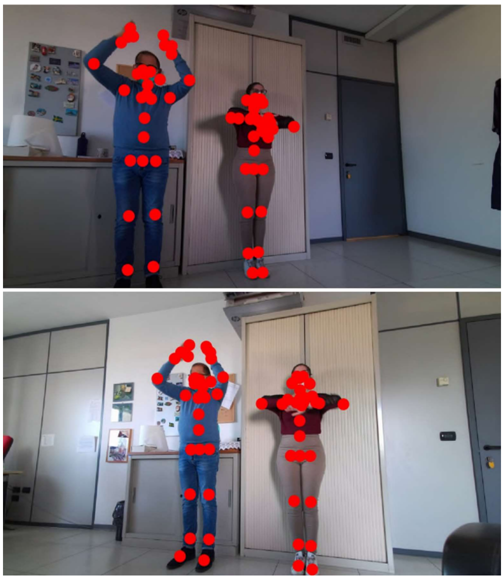

Fig. 3. Two RGB images captured from two synchronized Azure Kinect cameras looking at the same workspace. Here, two users are detected and tracked to obtain the corresponding skeletons.

Physical Energy Interpreter - In the proposed architecture, visual data is acquired using a set of RGB-D cameras looking at the workspace shared between the Worker and the MindBot Coworker from different points of view to contrast possible occlusions. In particular, the Microsoft Azure Kinect DK [21] cameras have been selected, since they can provide high image resolution, up to 2560×1440 pixels at 30 Hz. Moreover, the Microsoft Azure Kinect Body Tracking Library is leveraged to track users and estimate the 3D position of their skeletal joints with high accuracy and reliability, and low uncertainty [22]. For each camera, four topics are published to the ROS network delivering the compressed RGB image, the depth map, the depth map rectified in the color space geometry, and the skeletal data. Fig. 3 shows an example of two synchronized cameras looking at the same workspace and tracking the skeletons of two users. Note that recorded videos are encrypted via a 256-bit Advanced Encryption Standard (AES) to ensure the mandatory data security due to privacy reasons.

The obtained information is then exploited to perform an online computation of the kinematics and the dynamics of the upper-limb [23] following the inverse dynamic approach [24]. Articular angles, velocities, accelerations and torques are used to provide an estimation of the exerted joint power and energy expenditure. This data represents the basis of the estimation of measures and parameters of effort and fatigue during the use of the MindBot platform, including time-to-peak [25], range of motion alteration and effort related to energy expenditure. Furthermore, exploiting the NASA Anthropometric Tables [26] and tracked data, this module estimates the volumes occupied in space by the operator and sends them through ROS to the cobot controller for collision avoidance purposes, as represented in the right side of Fig. 4.

Social and Affective Interpreter - To support a pleasant working atmosphere, the MindBot platform has to adjust the interaction in the case of suboptimal mental states, such as fatigue, stress or boredom. To recognize such states from the the worker's social and affective signals, the mobile Android framework SSJ [27] is used, a Java-native solution for social signal processing fully compatible with modern mobile devices. The framework enables the recording, analysis, and recognition of human behavior based on social and affective signals such as gestures, postures, facial expressions, body movements, and emotional speech. To this end, SSJ allows to interface with and extract data from device internal and external sensors. It provides support for most standard Android sensors (camera, microphone, IMU, GPS etc.) as well as various external sensors (heart rate chest strap, fitness armband with pulse monitor, smartwatch etc.). Due to its modular architecture, the data processing in SSJ is performed through pipelines, which consist of a sequence of autonomous components that allow the parallel and synchronized signal processing. Additionally, SSJ supports machine learning pipelines for the execution of pre-trained models as well as on-device training of simple online learning classifiers, such as Naïve Bayes. This is especially useful for creating machine learning models that can be adapted to the individual worker behavior over time. Previous work [28] has shown that tuning a pre-trained model is feasible on the current generation of mobile devices. The cobot makes use of SSJ's on-device training capabilities to protect the workers' privacy while adjusting to their specific needs.

Psychological Interpreter - In order to assess the experience associated with human-cobot collaborative activities, participants will be administered the Experience Sampling Method (ESM), a procedure developed to study behaviour and the associated experience during their unfolding in real life, thus avoiding memory distortions [29] [30]. Participants will receive a tablet sending repeated random acoustic signals. In the experimental setting of cobot development, signals will be sent during the collaborative task with the cobot; in the workplace implementation of the system, 6-7 signals will be randomly sent to the worker during the waking hours. At each signal participants are expected to fill a short online questionnaire including (a) open-ended questions, aimed at collecting descriptions of the ongoing activity and related stake, location and social context; (b) a set of scales assessing the individual quality of experience associated to the ongoing task, by rating the level of cognitive, affective and motivational dimensions, including perceived activity related challenges and personal skills in facing them.

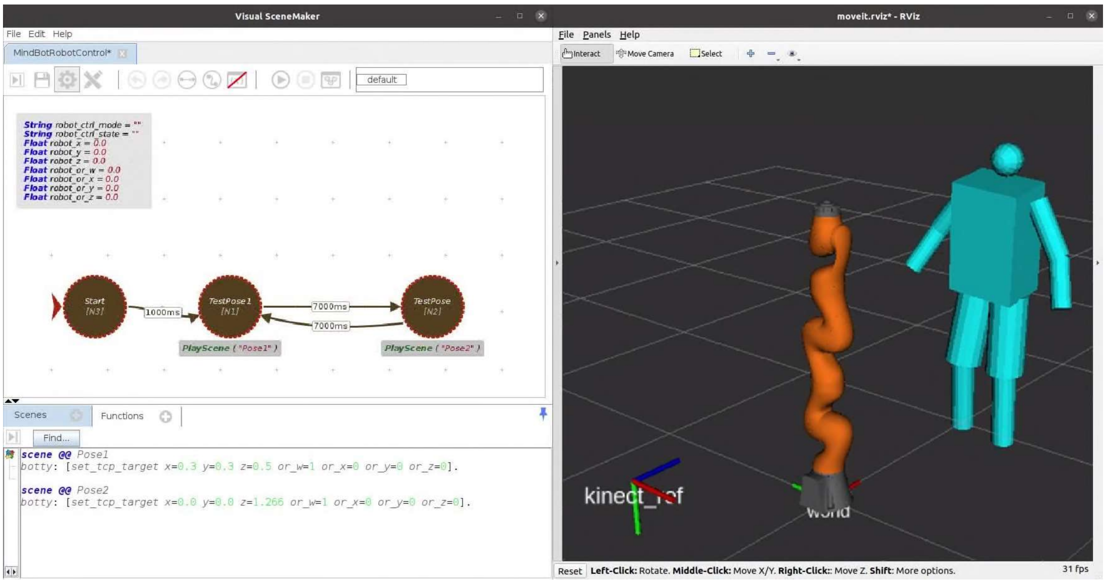

Fig. 4. Simulated example of the Orchestrator functionality. On the left, the logical organization of the task as programmed in VSM. On the right, the commanded Cobot and the volumes occupied by the Worker.

B. User Model

Emotions are not universally unique patterns (internally and externally) and are always connected to individual experiences. For instance, a smile could represent actual satisfaction in our work, but also a mechanism used to hide shame and insecurity. MindBot's Affective User Model (MAUM) allows cognitive modeling about estimated possible affective states and regulation strategies, such as avoidance, attack self, attack other, or withdrawal. MAUM is based on the MARSSI model [31], which comes with Dynamic Bayesian Networks (DBNs) to fuse multiple social signals. One of their main advantages is that they allow theory-based modeling of the structure and relevant features of a higher-level concept, such as regulation of shame with the regulation strategy withdrawal. Since DBNs support temporal representation, sequences for the interpretation of social signals can be learned. MAUM employs this DBN concept for real-time computation of a confidence value of possible modeled user affect, updating the possibilities of each modeled appraisal and regulation information. Note that MARSSI can be extended by different regulation strategies for persons diagnosed with autism spectrum disorders [32]. Moreover, for a computational representation of possible affective appraisal of the worker's context, environment, and task (e.g, deadline pressure, workplace noise, and monotony of work steps), the ALMA appraisal rules [33] are used. MAUM collects all stressors connected to mental focus or stress data measured by the subject's physiological responses and generates additional representations of affective states that denote the outcome of emotion regulation strategies. These representations can be seen as a basis for the real-time interpretation of social signals and environmental signals related to different regulation strategies for different types of people.

C. Orchestrator

The Orchestrator is a software framework for authoring, orchestrating, and executing scenario content with task specifications. In particular, relying on the content of the User Model, it is responsible for tailoring the actions of both the Cobot and the the Avatar coherently and consistently in order to obtain a resulting behavior for the MindBot Coworker adapted to the Worker's interaction experience. This component will be implemented using the Visual SceneMaker (VSM) tool [34], which comes with an authoring tool for creating interactive presentations aimed at non-programming experts. It supports modeling verbal and non-verbal behavior of interactive agents and robots through a graphical interface and a simple scripting language that allows domain experts to create rich and compelling content. VSM is open-source and implemented in Java 11 [35]. To achieve real-time communication with the Cobot, VSM is extended by a dedicated plugin that maps high-level commands on robot control commands using ROS communication protocols. A second VSM extension is a dedicated plugin that allows controlling the Avatar.

D. MindBot Coworker

The MindBot Coworker represents the integration of a Cobot, for the physical collaboration with the operator, and its corresponding Avatar, with social interaction purposes.

The **Cobot** is the physical executor of the commands generated by the Orchestrator. In particular, these commands are originated from the combination of two main drivers: the task to be carried out in the scenario under analysis and the high-level adaptation of the robot's motion to minimize the operator's stress level. Starting from raw trajectories, defined on the basis of the on-going task exploiting MoveIt! functionalities [36], actual trajectories will be refined depending on the psychological strain of the operator. The adaptation will occur in terms of parameters such as speed, acceleration, human-robot distance and robot configuration and commanded to the cobot within the *ros_control* framework [37]. For instance, starting from the information collected from the state of the art, here is the proposed adaptation for the robot's distance from the operator and movement duration:

$$d = \frac{C_1}{K} d_{min} \qquad (d_{min} < d < d_{max}) \tag{1}$$

$$t = \frac{C_2}{K} t_{min} \qquad (t_{min} < t < t_{max}) \tag{2}$$

denoting by:

- d the minimum distance from the worker while performing a trajectory;
- t the time taken to perform a specific movement;
- K an index representative of the mental state of the operator, according to the User Model, with $0 < K < 1$ supposing that $K = 0$ and $K = 1$ correspond to the operator's worst and best possible mental conditions respectively;
- C_1 and C_2 the operator's sensitivity to the variation of minimum distance and time, respectively;
- d_{min} a minimum value for the distance from the operator, set for safety reasons;
- d_{max} a maximum value for the distance from the operator, depending on workspace limitations;
- t_{min} a minimum time duration, set for safety and acceptability reasons;
- t_{max} a maximum trajectory duration derived from the productivity requirements of the cell.

It is important to underline that parameters as C_1 and C_2 will require a proper tuning and calibration of the adaptation logic through a proper experimental campaign. Moreover, the influence and regulation of the additional parameters listed before will be evaluated.

To implement this control logic, the knowledge of the operator's position inside the workspace is required. After a calibration phase, the simplified volumes occupied by the operator are integrated in the virtual planning scene, as represented in the right side of Fig. 4. This solution allows to actuate collision avoidance strategies with a limited impact on the system in terms of computational burden.

The **Avatar** is visualized through a real-time 3D interactive application running on the tablet (cf. Fig. 5). The Orchestrator provides the Avatar's behavior model to perform several actions: direct the gaze, perform gestures, pointing at entities in space, and talk. Role-wise, the Avatar acts as a mediator between the human and the cobot, filling the need for a humanoid shape to make robots more emphatic and acceptable. Conceptually, the Avatar can be considered as a virtual representation of the robot in humanoid form. Among its tasks, the Avatar will be responsible for proposing to the worker to complete ESM forms. For interactive sessions with the worker behaviors modeled to query users about his/her concerns and conditions when abnormal stress and fatigue levels are detected. A starting point is the supporting behavior model described in [38]. The Avatar visualizer is developed using the YALLAH framework [39], [40] that allows customization with the Blender 3D [41] editor and to deploy it on the tablet as a stand-alone Unity application.

Fig. 5. Example of virtual avatar running on tablet

V. CONCLUSIONS AND FUTURE WORKS

In the context of automated work, the risk of perceiving low challenges is extremely high for repetitive tasks; to the contrary, experiences of inadequacy may arise in workers exposed to tasks requiring unusually intense or sustained focus of attention and manual precision. Therefore, the possibility to identify cobot features that promote workers' engagement and flow experiences may open important research and application avenues. By virtue of their high level of adaptability to both context and human behavior, cobots can be exploited not just for their efficiency or human-like features, but also for their role in reducing the psychological strain or boredom workers may perceive in task performance. For these reasons, this paper presents a series of relevant parameters and software components exploited for the implementation of a human-driven control architecture.

This approach represents the starting point for the long-term goals of the MindBot project. Both lab-based and in-company experiments are currently being run to define the baseline parameters and the adaption logics required to complete the implementation of the system. Also, failure recovery strategies are being deployed to render the system as robust as possible. Future works will include the continuous improvement of the presented human-driven control structure together with the definition of additional behavior adaption algorithms aimed at minimizing the psychological strain experienced by the operator. Moreover, empathic movements of the Cobot arm will be integrated with the actions of the Avatar in a coherent and consistent fashion, and executed during non-productive phases of the interaction. Within that context, several studies (e.g., general acceptance of the Avatar, possible distractions, stress or boredom reduction, efficiency and flow increase) are planned. Organizational and technical guidelines will also be outlined for the design of a mental-health-friendly cobot-based manufacturing workplace. Regarding this topic, the role of the Organizer block in the control architecture is only mentioned within the paper, but could play an important role in deeply tailoring the task to the actual mental state of the operator.

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