A Methodology for Comparative Analysis of Collaborative Robots for Industry 4.0

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***Abstract*—Collaborative robots are one of the key drivers in Industry 4.0 and they have evolved considerably since the last decades of the 20th century. With respect to the industrial robots, collaborative robots are more productive, flexible, versatile and safer. In the recent years, many industrial robot producers and startups entered the segment of collaborative robots. In this paper, we propose a methodology for developing a comparative analysis of the collaborative robots currently available in the market. The goal of the paper is to provide a framework for allowing the benchmarking, based on common robot parameters and standardized experiments that can be performed with the robot under investigation. An experimental technological review of three different collaborative robots is provided, to show how the methodology can be applied in real cases.**

I. INTRODUCTION

The term Industry 4.0 was first introduced at the fair in 2011 in Hannover. It comes from the high-tech strategy of the German Federal Government that promotes automation-computerization to complete smart automation [1]. Recently, there has been an important growth of interest in industrial end users about the new possibilities of safe human-robot interaction, namely having humans and robot share a common workspace without physical fences on the factory floor and performing tasks in collaboration [2], [3]. As a result, collaborative robotics has been considered one of the enabling technologies of the fourth industrial revolution, within the Industry 4.0 program [4] and beyond. The introduction of such robotic systems in industrial applications poses two major issues, which cannot be ignored. Specifically, issues related to safety must be considered, since any harm to the human worker due to proximal interaction with the robot must be prevented. As a consequence, safety standards have been updated to address the new collaborative scenarios and the international ISO 10218-1 and ISO 10218-2 regulations [5], [6] have identified specific applications and criteria where collaborative tasks can occur. More recently, the technical specification ISO/TS 15066 [7] has been introduced to specify safety requirements for collaborative industrial systems and supplements the requirements and guidance on collaborative industrial robot operations given in ISO 10218-1 and ISO 10218-2. Additionally, issues related to human factors and cognitive workload for the user have to be considered. Indeed, shopfloor workers, who typically are neither expert nor confident with the use of robots, are requested to work close to such complex systems: this generates anxiety and fear [8]. Given the recognized importance of collaborative robotic systems, the major industrial robot producers such as KUKA, ABB, Fanuc, etc. entered the segment, while new high-tech companies and startups such as Rethink Robotics and Franka Emika grew up. Such a commercial scenario includes proposals very different from each other and, especially, from classical industrial robots, making it difficult for end users to compare them and select one.

The objective of this paper is exactly to address the latter issue, by providing an experiment-driven methodology for the comparative analysis of existing collaborative robots. To the best of our knowledge, there are no references in the literature presenting a similar approach to collaborative robots benchmarking. The proposed framework is easy to implement and can be exploited both by end users, to understand which collaborative robot can be suitable for their applications, and by robot manufacturers, to identify the need for new features or application-specific options. In particular, the main contributions of this paper are:

- The development of an application/user-oriented methodology for easily performing a comparative analysis of collaborative robots.
- An experimental technological review of three collaborative robots (KUKA LWR 4+, Universal Robots UR5, Franka Emika Panda), which provides an example of application of the proposed framework.

II. BACKGROUND ON COLLABORATIVE ROBOTICS

A collaborative robot is designed to share a workspace and physically interact with humans. Being such physical interactions potentially dangerous for human workers, early research and standardization works put a strong emphasis on safety. Then, ease of programming, a lightweight design and deployment flexibility have also been recognized necessary for a robot to be considered truly collaborative [9]. The great benefit of collaborative robotics is the possibility to combine the qualities of the human with the qualities of the robot, to improve the performance. Indeed, on the one hand, robots excel at simple, repetitive handling tasks, while humans, on the other hand, have unique cognitive skills for understanding and adapting to any changes in the task.

The safety of the human is an absolute prerequisite. In this direction, collaborative robots must incorporate novel technical features, allowing them to operate in one or more of the following modes, as defined by the safety standards ISO 10218-1/2 and the technical specification ISO/TS 15066:

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Safety-rated Monitored Stop (SMS), Hand Guiding (HG), Speed and Separation Monitoring (SSM), Power and Force Limiting (PFL). A brief and pictorial description of such operating modes can be found in [10]. From a robot control perspective, the modes classified as HG and PFL imply significative challenges, mainly related to the estimation (and consequent limitation) of contact forces, due to impacts or collisions between the robot and the human, and the distinction between intentional contacts (i.e. for guiding the robot by hand) and unintentional or harmful ones.

In terms of quantitative evaluation of the limits to be enforced on such contact forces, the Annex A of the ISO/TS 15066 collects results from relevant biomechanical studies on human pain levels and provides tables and formulas to be applied for risk assessment of a collaborative robotic application. In particular, for each use case of a given collaborative task the risk of quasi-static contacts (e.g. a part of the human body is trapped between the robot and a workpiece, while the robot pushes towards the workpiece) or transient impacts (e.g. a part of the human body is within the motion trajectory of the robot) should be evaluated. In the former case, the maximum force and/or pressure that can be applied by the robot depends on the human part involved by the contact, in the second case the force/pressure limit is a parameter in the computation of the maximum speed at which the robot can move when the risk of impacts is relevant. In both cases, it turns out that the capability of the robot to estimate and/or regulate and limit forces due to external contacts is a critical feature. Therefore, we will consider the evaluation of a collaborative robot accuracy on external force estimation as a central part of the benchmarking methodology described in the following section.

III. PROPOSED METHODOLOGY FOR COLLABORATIVE ROBOTS COMPARISON

The comparison of different commercial proposals should necessarily start from a review of relevant technical data, as declared from their respective manufacturers. Off-the-shelf robotic manipulators, in particular, can be analyzed in terms of payload, weight, positioning repeatability, size of the workspace and dynamic performances, generally given in terms of maximum speed of the joints or maximum Cartesian velocity of the end-effector. Such technical data allow to evaluate the compatibility of a given robot with the operational requirements of a specific application and their interpretation is well-known by any industrial robotics specialist.

However, collaborative robots should be compared also in terms of other features, possibly less familiar to industrial technicians, and according to a different perspective. Indeed, robot capabilities such as the limitation of speed and forces to minimize the effects of an impact between the robot and the human are dictated by the international regulations and require a quantitative evaluation. This evaluation has to take into account not only the robot-dependent technical data, as declared from the manufacturer, but also peculiar aspects of the expected application and its related risk assessment. In particular, the guidelines provided by the ISO/TS 15066 prescribe to address the risk of quasi-static contacts by evaluating the force/pressure applied by the robot, while in case of a transient impact the concern is on the speed of robot motion. The speed limit is related to the prescribed limit on force/pressure on a given human part (see [7] Annex A, Table A.2), but also to the effective mass involved in the impact, depending on the human part again and on the mass of the moving parts of the robot, including the payload (see [7] Annex A for details). Of course, the payload and the moving parts of the robot depend on the task of interest for a given application.

Finally, collaborative robots dramatically changed the way in which tasks and applications are programmed on the control units, thanks to hand-guiding and teaching-by-demonstration modes [11], [12]. In these operating modes, the user perspective is very important. More precisely, the physical effort required by the user to drag the robot into the desired poses, and the cognitive load, required to record such poses on the control program, design the corresponding execution logic and handle the physical interaction with the robot, are factors to be considered in a comparative analysis. The physical effort can be measured with force/torque (F/T) sensors, while the cognitive load requires a subjective evaluation, that can be collected asking a set of users to fill in a questionnaire on the usability of the robot and its programming interface. In addition, some physiological parameters (e.g. heart rate variability) can be acquired from portable devices and processed to quantify the stress level of the user during the interaction, as shown in [8].

Summarizing, a proper comparison of different collaborative robots should take into account robot-dependent aspects (i.e. technical data and experimental verification of declared features), application-dependent aspects (i.e. force/speed limits for risk assessments) and user-dependent aspects (i.e. perceived usability, physical/mental effort for teaching and programming). Being the desired application quite relevant in the comparison, the first step of our benchmarking methodology is the specification of a demonstrative task, that should emulate the actual application, but should also be programmed and executed in shorter times and equipping the robots with rapidly prototyped tools. For the illustrative purpose of this paper, we considered a task requiring the robot to pick objects of different shapes from a positioning mask and place such objects into another mask, in the right position, using a simple 3D-printed cylindrical handle ending with a permanent magnet as the grasping tool. The reader may refer to the following video for a complete presentation of the demonstrative task: https://streamable.com/pzrqq.

As a second step in the methodology, we analyse the safety-related features of the robots by focusing on the PFL collaborative mode. This focus allows to consider only proprioceptive sensors (i.e. joint torques or motor currents) and their processing in the proprietary robot controller, without introducing optional external equipments possibly required for SMS and SSM modes. To verify the reliability of PFL features, we suggest to mount a 6-DOF F/T sensor between the robot flange and the operating tool and measure the interaction forces during both hand-guided teaching operations and impact tests. Concerning the latter, building a specific impact force/energy measuring device (as in [13]), is a very interesting alternative option, that will be considered in a future extension of the present work. Measurements from the wrist-mounted F/T sensor are also needed to verify the accuracy of the external force estimation embedded in the robot controller and to quantify the physical work and force required to the user during hand-guidance. For this purpose, users involved in the programming task were instructed to grab the robot only from the tool for hand-guiding, while the transient impacts were evaluated in contacts between the tool and the hands of the volunteers.

It is important to remark that the accuracy of both the proprietary estimation of external forces and auxiliary F/T sensor used for validation strongly depends on a precise calibration of the payload inertial properties, preferrably executed online to be adaptive [14]. To obtain a fair comparison, we used the same tool, F/T sensor and mounting assembly on each robot under test and we calculated the inertial properties of such assembly from CAD geometry, then we used such parameters for the configuration of each robot controller and for compensating F/T sensor measurements, as shown in [15].

The final step of the proposed comparison methodology is the execution of benchmarking experiments, as follows:

1) Evaluation of quasi-static impact tests, verifying the maximum force exerted by the robot while pushing on a rigid obstacle (e.g. the operating table) at different distances from its mounting base (e.g. 25%, 50% and 75% of the workspace radius), trying to reach a position beyond the obstacle itself.

2) Evaluation of quasi-static impact tests, verifying the maximum force exerted by the robot in the first impulse of the impact with a human part (e.g. the hand), corresponding to the total energy transfer according to inelastic contact model considered in the ISO/TS 15066. Since the test is only for benchmarking ad executed on human volunteers, the speed of the robot must be bounded at half of the limit resulting from the application of Formula A.6 of the ISO/TS 15066 [7], Annex A.

3) Evaluation of task programming effort and usability. The programming effort is evaluated from:

- time to complete the task control program, including teaching of poses and writing the software code in the robot programming environment[1];
- force and energy required to the user for the hand-guided teaching of the given task;
- stress level, as detected by monitoring heartbeat rate variability with a portable device [8].

Usability is evaluated asking the users to fill a questionnaire defined by merging the general-purpose System Usability Scale (SUS, [16]) and the Questionnaire for the evaluation of Physical Assistive Devices (QUEAD, [17]), specifically designed for human-robot interactive applications.

IV. METHODOLOGY IMPLEMENTATION AND RESULTS

The methodology described in the previous section has been implemented for the comparison of three collaborative robots from different manufacturers. The selected robots represent a first interesting sample of the collaborative robotics market, including commercial proposals with different and somehow complementary features. In the following, we briefly describe the robots used for benchmarking experiments, referring the reader to the official documentation and datasheets provided by the respective manufacturers for full details.

KUKA LWR 4+: it is a 7-DOF manipulator with a particulary efficient (i.e. 7 to 16 Kg) weight-to-payload ratio (indeed, LWR stands for LightWeight-Robot), rounded shape of its mechanical links and housings (reducing its harmfulness for humans) and integrated joint torque sensors (allowing the implementation of accurate estimation of external contact forces and compliant control schemes). The design of the KUKA LWR 4+ has been recently refined into the one of the KUKA LBR iiwa, which is fully certified for collaborative industrial use (the LWR 4+ is instead not certified). Up to now, the LBR iiwa is one of the most representative example of a tecnhologically advanced, but expensive, collaborative industrial robot, which naturally motivates its selection for the proposed benchmarking. However, since an LBR iiwa was not available during our experimental campaign, we will report results obtained using an LWR 4+, whose technology is largely similar to the one of the LBR iiwa. Major differences between the two systems are the safety-related functions and the control hardware/software: the LWR 4+ adopts a customized version of the classical Kuka Robot Controller (KRC), programmable with the KRL language, while the LBR iiwa has a newer control architecture called Sunrise, programmable with Java.

Universal Robots UR5: a 6-DOF manipulator with a 5 kg payload, a user-friendly and industry-oriented programming interface and particularly competitive performance-to-price ratio. Indeed, it is estimated that Universal Robots, producing also the smaller UR3 and the larger UR10 robots sharing the UR5 technologies, is currently the leading manufacturer on the collaborative robots market, producing more than 50% of the totally sold units [18]. The latter is the aspect that mainly motivates the selection of a UR5 for benchmarking. Moreover, UR5 robots are programmed by means of a portable touch-enabled device and its software interface called Polyscope, supporting a very simple textual programming language. This programming approach is a usual practice for industrial technicians.

Franka Emika Panda: a 7-DOF manipulator with a 3 kg payload and mechatronic design particularly oriented to minimize its end price. Indeed, the Panda robot is the cheapest redundant and collaborative robot currently available on the market, even though it must be said that the version certified for industrial use is available since a few weeks at the time of writing and, therefore, a previous version only usable for academic research has been used during our experiments. However, the industrial version adopts the same unique icon-based

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[1] To fully understand the ease of use of each robot, users were not previously trained on the respective programming interface, but they were given a specifically written programming guide at the beginning of the experiment.

programming environment called Franka Desk, executable by simply connecting any web browser to the Ethernet port on the robot's base. The novel and low-cost technology of the Franka Emika Panda is the main reason for including it in the comparison.

A. *Experiments on KUKA LWR 4+*

Even though the KUKA LWR 4+ is not certified for collaborative industrial use, it supports physical Human-Robot Interaction (pHRI) thanks to the activation of either impedance control mode (in either Cartesian or joint space) or gravity compensation, which allows hand-guidance for teaching purposes. Whatever control mode is active, the robot controller is always able to estimate external forces at the end-effector, thanks to an embedded torque sensor on each joint. At first, we evaluated the accuracy of such a force estimation by comparing its outputs with the measures of the ATI Mini45 F/T sensor mounted on the robot wrist, considered as the ground truth. Figure 1 shows values of the force component on the Z-axis of base frame during a teaching activity in gravity compensation mode, in which the user moved the robot inside the workspace and at different velocities. As can be seen, the estimates are quite accurate (less than 1 N of RMS error).

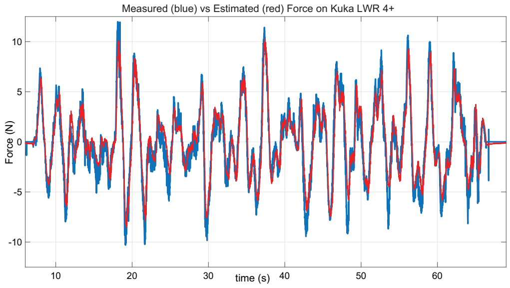

Fig. 1. Comparison between measured (blue plot) and estimated (red plot) external forces: Kuka LWR 4+

Then, ten users selected among students and researchers of the University of Modena and Reggio Emilia were asked to fully program the pick and place task previously described, without any previous training and with the only help of a brief programming guide specifically written by the authors. For each user, we collected: time taken to write the control program and teach the required poses; forces applied on the tool (both measured and estimated, to fully characterize the accuracy of the latter); stress level detected from the portable device; usability score from the hybrid SUS/QUEAD questionnaire.

Concerning the validation of safety features, we considered the execution of positioning tasks in impedance control mode, which means that the robot indirectly regulates the contact force according to a configurable stiffness. It is also possible to configure a maximum force, separately on each motion coordinate. However, if such a maximum force is reached, the robot does not trigger a safety stop. As a result, the behavior of the robot during the quasi-static impact test is the one presented in Figure 2. The robot has been moved in contact with the environment and programmed to proceed its motion. The exerted force rapidly achieves the configured limit, set to 100 N to allow a comparison on all the three robots. Then, the limit force is maintained indefinitely. The observed behavior does not vary significatively in different parts of the workspace, provided that the joint configuration is far from singularities.

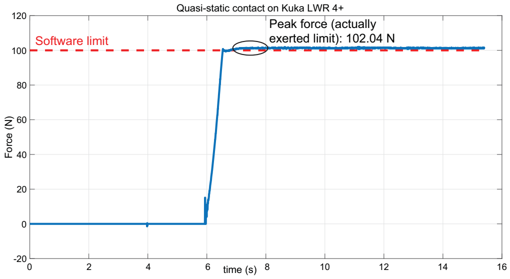

Fig. 2. Measured force during a quasi-static impact test: Kuka LWR 4+

Finally, we verified the peak force applied by the robot on an impact with a human hand, while moving along a linear trajectory in Cartesian space at a speed of 685 mm/s, calculated according to the guidelines of ISO/TS 15066 Annex A, but with the aim to limit the energy transferred at the impact to half of the admissible maximum. Such energy corresponds to an expected peak value of the force at the impact of 140 N. As can be seen from Figure 3, the force actually measured during this test is much smaller, which is a reasonable result considering that the values proposed by the ISO/TS 15066 are quite conservative. On the other hand, the plot is consistent with the qualitative example provided by the ISO specification, highlighting an initial impulse due to the transient impact and a phase with almost constant force, corresponding to the dragging of the human part in contact with the robot.

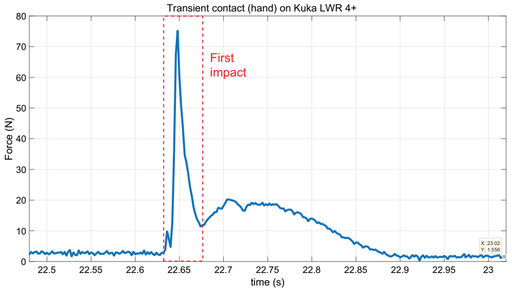

Fig. 3. Measured force during a transient impact test: Kuka LWR 4+

B. *Experiments on Universal Robots UR5*

The Universal Robots UR5 is currently the best seller of collaborative industrial robots, natively supporting safe enforcement of limits on force, power and speed, and allowing hand-guided teaching with its so-called Freedrive mode. Programming commands include direct force regulation, executable when the robot is in Force mode. However, the standard UR5 is not equipped with neither F/T sensor at the wrist nor joint torque sensors, so that both Freedrive and Force modes are implemented relying on standard feedback signals (i.e. joint positions and motor currents) and model-based processing. Not surprisingly, using this lower cost technology the UR5 is not as accurate as the KUKA LWR 4+: its RMS error on external force estimation is more than 13 N, with a peak of 55 N. Another interesting aspect of the UR5 force estimation is the fact that in Freedrive mode it does not reflect the force actually applied at the end-effector, as shown in Figure 4, while in Position or Force mode it does. The reason for this mismatch is not documented by the UR5 operating manual.

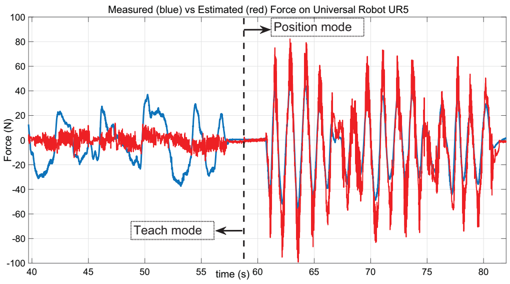

Fig. 4. Comparison between measured (blue plot) and estimated (red plot) external forces: Universal Robots UR5

To cope with this issue, the data for estimation accuracy verification where not collected from user programming tests, as for the KUKA LWR 4+, but from interaction tests in static conditions and at different configurations of the arm (avoding singularities and joint limits). The interaction forces applied during teaching by the users (a set of ten students and researchers of the University of Modena and Reggio Emilia, partially overlapped with the group experimenting the KUKA robot) were instead measured by the wrist-mounted ATI Mini45 sensor. Such measurements revealed that the physical effort required to the user by the UR5 is significatively higher than the one required by the KUKA LWR 4+.

On the other hand, the quasi-static impact tests confirmed that the UR5 is able to properly trigger a safe stop when the external force approaches the configured limit, taking into account the uncertainty in its force estimation thanks to a conservative threshold, as shown in Figure 5.

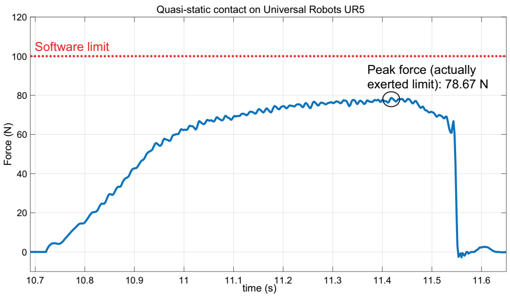

Fig. 5. Measured force during a quasi-static impact test: UR5

We do not include plots of transient impact tests on the UR5, actually quite similar to those obtained on the KUKA robot, due to space constraints.

C. Experiments on Franka Emika Panda

The Franka Emika Panda (research version) contains technologies comparable with those of the KUKA LWR 4+, at least from datasheet, at a price comparabile with that of the UR5. Thanks to the presence of joint torque sensors, the external force estimation is quite accurate (less than 1.5 N of RMS error) especially during dynamic motions, as shown by Figure 6. At rest, the estimate is slightly biased, possibly due to a non-perfect calibration of static friction effects.

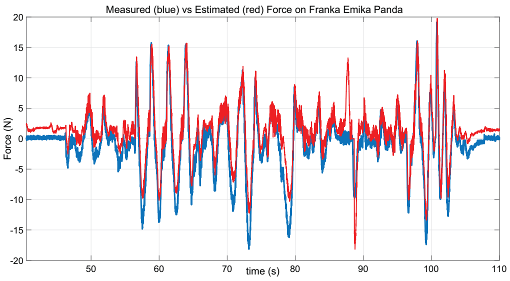

Fig. 6. Comparison between measured (blue plot) and estimated (red plot) external forces: Franka Emika Panda

The accuracy of the Panda controller is also reflected by the smooth behavior of the robot in teaching mode. Indeed, the programming experiments performed by ten users, selected among students and researchers of the University of Ferrara, showed that the Panda robot can be dragged manually with minimal efforts and that even complex tasks can be programmed rapidly and easily, thanks to its web-based graphical interface and its icon-based language. Another major peculiarity of the Panda is the fact that the only buttons enabling teaching mode are mounted on the robot wrist. This feature further improve the robot usability, but is also counter-productive for our comparison. In particular, we had to block the teaching mode buttons with a clamp, so that users were forced to interact with the robot by grabbing only the tool mounted after the ATI Mini45 F/T sensor.

Even if the safety-related features of the Panda research version are not certified for industrial use, the quasi-static impact tests always led to a prompt and reliable reaction to the violation of programmed limits on Cartesian forces and joint torques, as shown by the example plot of Figure 7. Plots taken from transient impact tests are omitted, due to space constraints.

D. Final comparison and discussion

The quantititive results of the benchmarking experiments are reported in Table I. In brief, we can highlight that the Franka Emika Panda is easier to use and at the same time its safety-related features are reliable enough to enable collaborative applications. On the other hand, the programming interfaces of KUKA and Universal Robots are based on older design concepts, but just because of this they are also more adequate for the industrial practice. Indeed, it is also important to remark

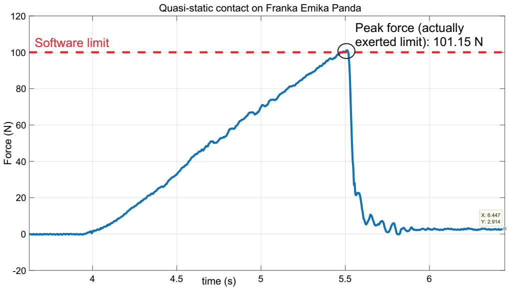

Fig. 7. Measured force during a quasi-static impact test: Franka Emika Panda

that the results of the usability score is necessarily affected by the background of selected users. If the latter were sampled from industrial control engineers or technicians, the traditional look and feel of LWR 4+ and UR5 portable teach pendants (totally missing on the Franka Emika Panda) could have been more appreciated.

Finally, we should emphasize that the behavior of all the robots during both quasi-static and transient impact tests turned out to be compliant with the ISO/TS 15066 requirements, even if neither the KUKA LWR 4+ nor the Panda research version that we tested are marketed as ready for the industry.

TABLE I

SUMMARY OF THE COLLABORATIVE ROBOTS FEATURES AND BENCHMARKING EXPERIMENTAL RESULTS

	KUKA	**UR5**	**Panda**	
Technical data				Units
Payload	7	5	3	Kg
Weight	16	18.4	18	Kg
Repeatability	±0.05	±0.1	±0.1	mm
Joint ranges	±120/±170	±360	±95/±166	deg.
EE speed	N/D	1000	2000	mm/s
Workspace radius	868	850	855	mm
Task programming				
Completion time (avg.)	27.2	25.7	12.7	min.
Hand-guiding work (avg.)	4.0	24.0	4.12	J/min.
Hand-guiding force (max)	14.5	41.1	7.65	N
User stress level	59.3	43.0	47.6	%
Usability score	63.0	62.4	85.4	%
Force estim. error (RMS)	0.96	13.54	1.46	N
Force estim. error (max)	7.64	55.49	18.07	N
Quasi-static impact				
Force limit range	0/200	100/250	10/100	N
Max measured force (with 100 N limit)	102.04	78.87	101.15	N
Transient impact				
EE speed limit	685	680	683	mm/s
Max measured force	75.14	28.55	56.78	N

V. CONCLUSIONS

The paper has presented a methodology for a task-oriented comparison of collaborative robots and the application of such a methodology to a demonstrative set of robots. The proposed methodology takes into account the ISO 10218-1/2 and ISO/TS 15066 standards, but it is not intended to support a full risk assessment. Indeed, the latter may require to evaluate aspects that go beyond the pure comparison of robot technologies.

Future works will enlarge the set of robots involved in the experimental analysis, starting with certified versions of some of the robots described in this paper (i.e. KUKA LBR iiwa and the newer Franka Emika Panda with CE-ready application modules). Another aspect that deserves further investigation is the precise quantification of the energy transferred during transient impacts, by means of specifically developed testing devices and more accurate mathematical models of the human-robot contact.

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