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End-point Impedance Measurements at Human Hand during Interactive Manual Welding with Robot*

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Abstract—**This paper presents a study of end-point impedance measurement at human hand, with professional and novice manual welders when they are performing Tungsten Inert Gas (TIG) welding interactively with the KUKA Light Weight Robot Arm (LWR). The welding torch is attached to the KUKA LWR, which is admittance controlled via a force sensor to give the feeling of a free floating mass at its end-effector. The subjects perform TIG welding on 1.5 mm thick stainless steel plates by manipulating the torch attached to the robot. The end-point impedance values are measured by introducing external force disturbances and by fitting a mass-damper-spring model to human hand reactions. Results show that, for professionals and novices, the mass, damping and stiffness values in the direction perpendicular to the welding line are the largest compared to the other two directions. The novices demonstrate less resistance to disturbances in this direction. Two of the professionals present larger stiffness and one of them presents larger damping. This study supports the hypothesis that impedance measurements could be used as a partial indicator, if not direct, of skill level to differentiate across different levels of manual welding performances. This work contributes towards identifying tacit knowledge of manual welding skills by means of impedance measurements.**

I. INTRODUCTION

In this paper we perform end-point impedance measurements at human hand during a realistic manipulation task, manual welding, which is an indispensable process in many branches of industry [1]. Despite its importance, the skill that is required to perform good welding is tacit. A manual welding course lasts 20 to 40 weeks and around 85% of the time is devoted to welding practices [2]. The tacit skills are learned implicitly first in such practice hours and then throughout the initial years of professional work [3]. The impedance measurement techniques developed in domains such as human physiology, physiological rehabilitation, and human-robot interaction [8-15] might be applied for quantifying the tacit skills of welding. This study is a first attempt to perform impedance measurements with professional and novice welders.

A first approach to quantifying differences in kinematic pattern of motion across skilled and unskilled welders was presented in [4]. It was shown that skilled welders were more stable with the motion of the welding torch. Our previous work [5, 6] made a first step towards classifying between skilled and unskilled welding performances based on the variation of high frequency components of position signals. Afterwards, the findings inspired us to develop a robotic assistance for manual welding where damping was used to suppress vibrations [7]. In these works, the interaction forces between the human hand and the torch were not studied; therefore we did not have any idea about how the welders reacted to the vibrations during welding. This knowledge might be useful to develop more sophisticated and adaptive robotic assistance for manual welding. The present study focuses on this force interaction by analyzing how human hand reacts to disturbances.

Human arm joint impedance or human end-point hand impedance can be measured by introducing either position [8, 9, 10, 11] or force [12, 13, 14, 15] disturbances. In this work we follow the force disturbance approach; because it is conveniently applied for manual welding, where the welding line is not pre-programmed and it might even dynamically change according to the working style of the welder.

Impedance is usually measured when the human performs either position control, e.g. holding a handle at a reference position [10, 13, 15, 16, 17, 18], or trajectory control, while the hand is moving a handle from one point to another [8, 9, 12]. In the latter case, a reference trajectory is used either for calculation of a reference position [8, 9] or for guiding the movement with a visual interface [12]. In [9], the authors apply artificial force fields and observe the impact of learning on arm impedance. Through learning, the subjects increase their end-point stiffness in order to counter the divergent force field. In [15], the authors measure the end-point impedance while the subjects apply different grasp force on an object while positioning it at a given location.

In the above studies the tasks are constructed for the purpose of the experiment and do not relate directly to a real-world application. Manual welding differs from those as it requires intense concentration and fine positioning under the conditions of the metal melting at high temperatures, noise arising from the welding equipment, a helmet allowing to see only the welding region, and the necessity to continuously monitor the process to achieve a good performance. For the experiments of this study, the novice subjects were briefly instructed about the process of welding, such as the melting conditions and how the melted part should look like for a good weld. A demonstration of welding was also performed to show these in practice. The

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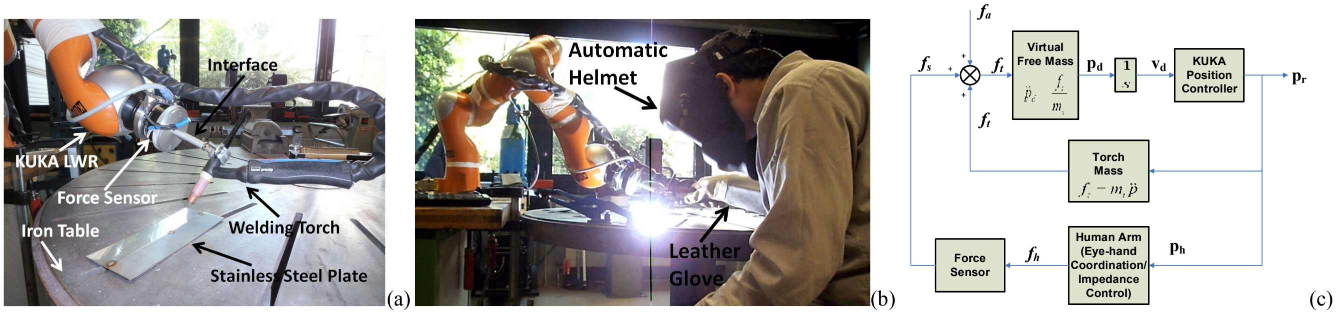


Fig. 1. Experimental setup for the interactive manual welding with the KUKA LWR robot. (a) The robot end-effector, force sensor, interface, welding torch, iron table and stainless steel plate are shown. (b) The use of the system by the subject is shown while performing TIG welding; the automatic helmet and leather glove are indicated. (c) Block diagram for interactive control of the KUKA LWR and for impedance measurements.

subjects were instructed to aim at a good quality weld along the line that connects the two pieces of metal plate. They were left free to move their body as they felt most comfortable, and to adapt the speed and position of the tool as they felt best to achieve a good performance.

There are a handful of studies that perform impedance measurements in real-world tasks. In [19] the authors work on calligraphy drawing. They perform real time estimation of end-point arm stiffness based on the differential force and position values, for the purpose of adapting the damping of a collaborating robot. In [20], the end-point arm impedance is measured during virtual tennis playing. The authors state that the subjects prepare for the motion of hitting the ball by increasing hand stiffness. Although these studies make impedance estimation/measurement with real-world tasks, they do not provide comparative measurements across different types of performances. In the present study we perform measurements across professional and novice welders and compare the results.

II. EXPERIMENTAL SETUP AND SUBJECTS

The interactive manual welding system, shown in Fig. 1(a, b), is composed of the KUKA LWR robot, an ATI force sensor attached to its end-effector, and a standard TIG Welding setup. The welding torch is attached to the force sensor via an intermediary structure (interface). The subject manipulates the welding torch to weld the two stainless steel plates on the iron table along their touching edges.

The KUKA LWR is a 7 degrees-of-freedom light-weight robot (16kg) designed for physical human-robot interaction. The robot is controlled through a dedicated Robot Controller Box and a Fast Research Interface (FRI). In this study the robot is admittance controlled using the force sensor (Fig. 1(c)). The sensor monitors the forces applied by the human hand; the position is updated according to these forces.

The admittance controller emulates a virtual free floating object at the end-efffector (Fig. 1(c)). Under nominal conditions (with no artificial force, $f_a=0$), the force sensor reading is used to manipulate the position of the end-effector. A virtual mass (m_v) of 2kg is used to transfer the force signal into a velocity command to the position (velocity) controller. The Robot Controller Box, indicated as KUKA Position Controller in Fig. 1(c), provides 3 kHz servo-control cycle rate locally in the joints. The FRI provides 1 kHz overall servo-control cycle rate, for communication of the desired velocity (v_d) between the controlling computer and the control box. The force signal is also sampled at 1kHz. In the absence of any artificial force ($f_a=0$), the human feels like manipulating the virtual mass in free space, without any gravity impact. The velocity command to the position controller is generated according to the virtual mass dynamics taking into account the force applied by the human (f_s) and compensating for the inertial force (f_t) on the tool (torch), the mass of which is 0.3 kg.

The TIG Welding setup is a standard one daily used in mechanical workshops. In the experiments the subjects performed straight line welding on 1.5 mm thick stainless steel plates (Fig.1 (a)) with 40 Amperes DC current. Manual welding necessitates wearing a helmet with special eye protection and leather gloves to protect the skin from the ultraviolet radiation in the vicinity of the welding arc (Fig. 1(b)). The TIG welding in our experiments was without any external feed, meaning there were no sparks and molten metal particles spreading around.

In these experiments the subjects performed welding with the robot in four different phases. In phase-I the subjects familiarized with the robot and the welding process. In this phase they performed welding freely on the metal plate and experienced for the instructed proper melting of metal to achieve a good weld. This phase lasted as long as the subjects got used to the system and felt confident with welding. In phase-II, the subjects performed normal interactive welding, without any disturbance.

In phase-III the subjects performed welding with disturbances. They were informed that there would be disturbances. The disturbances composed of 100 ms duration 3 N force impulses, randomly applied in one of the five (±*x*, ±*y*, +*z*) directions. The impulses were introduced at random instances, making sure that there was at least 10 seconds duration between two successive impulses. The welding session in phase-III lasted around 110-120 seconds. Phase-IV was a repetition of phase-III. Together in phase-III and phase-IV, we gathered data from 12 disturbances for each subject, four for each of the *x*, *y*, and *z* directions.

The force data used for our measurements was passed through a low-pass filter with 20 Hz cutoff frequency (third order Butterworth filter) in order to eliminate sensor noise. This cutoff value was considered to be large enough to capture the human force reactions as it is above the bandwidth that is required for meaningful human force perception (15 Hz is noted to be enough) [21], and as the same or lower values were used in some other studies [11, 10, 17, 22]. The velocity and acceleration signals were generated from the position signals by numerical derivation using backward difference, and low pass filtering with 10 Hz cutoff frequency. The spectrum of the position signals included no significant power above 10 Hz.

In this study we are interested in the average end-point hand impedance applied throughout the welding line. Therefore, we do not perform measurements at specific locations or with specific arm configurations, as it is done in other studies [28, 29, 12, 23]. In these works, the body of the subject is usually restrained by straps in a chair and the forearm of the subject is placed in a molded plastic cuff [29]. Therefore, a specific location in the workspace corresponds to a specific arm configuration. In our case, it is not desirable to limit the movement of the subject, because we are interested in the best performance of each subject for welding. The subjects were instructed "to do their best for a good welding", which means they were free to choose the arm and body configurations. Our question was "what is the resulting average impedance on the welding line". Therefore, in our experiments we applied disturbances at random locations on the welding line.

Five professional and six novice welders took part in our experiments. However, two of the professionals did not adapt to the robotic system. One of them demonstrated too much position variation and the other demonstrated abrupt movements after disturbances. Therefore we present the results of the other three professionals and the six novices. The novice subjects were recruited among the PhD and post-doc researchers in our research group. These novice subjects did not have any prior experience in welding, except for experiencing it once or twice during their practical courses in their bachelors. The professional welders were recruited from the mechanical workshops of EPFL. They had either prior or current TIG welding experience as a part of their daily job. Besides the skills and experience in welding, the remarkable difference between the professional and novice subjects was that the former had larger and more muscled arms due to their daily manual work.

III. PERFORMANCE MEASURE

Interactive welding with the KUKA LWR differs from normal manual welding that professional welders are used to. Professional welders usually stabilize their welding arm by placing it on the table. This is not possible with the interactive welding because of the limited closed loop bandwidth of the robot. If the arm holding the torch touches the table, the interaction with the robot resembles a hard contact and causes the robot to shake at the end effectors. This difference was the main cause that two of the professional welders did not adapt to the interactive system. For the other three professionals and the novices, it was possible to adapt by exercising during the phase-I of the experiments. Since we are comparing novice welders with the professionals, we may hence wonder whether the three professional welders still realized their skills and performed better than the novices during interactive welding.

In our previous work [5] we demonstrated that kinematic variation of the tip of the torch can be used as a performance criterion to distinguish across skilled and unskilled welders for normal welding (without the robot). In the present study we use the same performance criterion to see whether the three professional subjects still perform better than the novice subjects when performing welding with the robot in phase-I. If we observe less variance with the professional welders, as it is the case with normal welding without a robot, then we can conclude that the professionals demonstrate skillful welding also with the interactive welding with robot. We pass the position signals through a high pass filter with 0.5 Hz cutoff frequency to eliminate the slow variations, such as the linear increase of position along the direction of the welding line (*y*) (Fig. 3(b)). Afterwards, first we calculate the variance of the three components of the position signal and then we calculate the variation of the magnitude of the position as in (1-3), where $p_{i,f}$ stands for the filtered *ith* component of the position signal, p_n for the reconstructed magnitude after filtering the signals, *v* for the value of variation, and *N* for the number of data samples.

$$v = \frac{1}{N-1} \sum_{i=1}^{N} (p_n)^2 \quad (1)$$

$$p_n = \sqrt{{p_{x,f}}^2 + {p_{y,f}}^2 + {p_{z,f}}^2} \quad (2)$$

$$p_{i,f} = high\_pass\_filter(p_i, 0.5\ Hz) \quad (3)$$

The phase-II experiments do not include any disturbance; therefore we can use a continuous duration of 80 seconds (between 20-100 seconds) for variance and variation calculations. The results are given in Table I for each subject. The novices demonstrate in average more variance in all three components. We observe that the average variation is smaller for the professionals than for the novices. There is only one novice, N2, who demonstrates slightly less variation than two of the professionals. All the other novices demonstrate more variation than all professionals. This is an indicator that in average the three professionals perform better than the novices with the interactive system. We also observe that both professionals and novices demonstrate minimum variance in *x* direction, middle range in *y* direction and maximum in *z* direction.

In Fig. 2 we present the photos of interactively welded metal plates in phase-II experiments by the professional subject P1 (a) and the novice subject N4 (b). In these photos, the better quality of the weld by the professional subject is visible. The line of welding and the thickness of the weld of the professional are more regular. The weld of the novice subject makes a lot of zigzagging. These are indications of the better control of the movement in *x* direction (less variance) by the professional welder. The dark spots on the weld by the novice subject occur because of irregular and

TABLE I

VARIANCES AND VARIATIONS OF POSITION FOR THE UNDISTURBED WELDING SESSIONS (HIGH-PASS FILTERED WITH 0.5 HZ, UNIT: MM)

Professionals					Novices				
	variance			variation		variance			variation
	x	*y*	*z*	*v*		*x*	*y*	*z*	*v*
P1	0.065	0.372	0.436	0.872	**N1**	0.139	0.641	0.741	1.520
P3	0.069	0.436	0.473	0.977	**N2**	0.119	0.344	0.477	0.939
P4	0.177	0.296	0.543	1.016	**N3**	0.078	0.477	0.751	1.306
					N4	0.119	0.404	0.769	1.291
					N5	0.070	0.432	0.524	1.026
					N6	0.206	0.653	0.639	1.499
Average	**0.104**	**0.368**	**0.484**	**0.955**	*Average*	**0.122**	**0.492**	**0.650**	**1.264**
Std.dev.	0.064	0.070	0.055	0.075	*Std.dev.*	0.049	0.128	0.126	0.239

improper melting of the metal. This is an indication that the novice subject did not maintain a regular speed and height as the professional (more variance in *y* and *z* directions).

With similar variation analysis, we demonstrated for the phase-III and -IV experiments that in the 5 seconds period before each disturbance, the variation of position was on the same level as those for the phase-I experiments (without disturbance). (This analysis is not presented here due to page limitations). This means that the 100 ms disturbance in our experiments was short enough for a fast recovery of the normal welding pace after the disturbance. Therefore the presence of disturbances in phase-III and -IV did not cause a significant difference in welding performance at the measurement instances. As a result, we can assume that the impedance values measured with disturbances in phase-III and -IV are representative of the welding performances without disturbances in phase-II.

IV. CAPTURING AND MODELING THE IMPEDANCE

Mechanical impedance describes the relation between an external force and the position of the system. We are interested in the end-point impedance, at the junction between the human hand and the welding torch. Therefore, the end-point human hand impedance in this paper refers to the overall Cartesian impedance generated together by the impacts of the shoulder, elbow, ankle joints, the soft tissue of the hand, and the leather glove worn by the subject.

The impedance measurement is performed by introducing external forces that exceed the nominal force required for the task around one order of magnitude. The subject applies a low nominal force to manipulate the torch along the welding line. When there is an artificial force (f_a) (acting in the time window [t_d, t_e]) (4), much larger than the nominal force, the robot acts basically under the control of the former and generates an abrupt motion. There is a short period of around 100 ms [25] during which the human cannot react voluntarily to generate forces to counter the abrupt motion. In this paper, for our calculations we consider the period of 200 ms ([t_d, t_w]), instead of 100 ms, and assume that any voluntarily action in this 200 ms period is negligible compared to the passive impedance reactions. The use of a larger period than 100 ms is because the variation of the collected data in 100 ms period is not enough to calculate physically meaningful (all positive) impedance values in a consistent way (more than 90% of the cases).

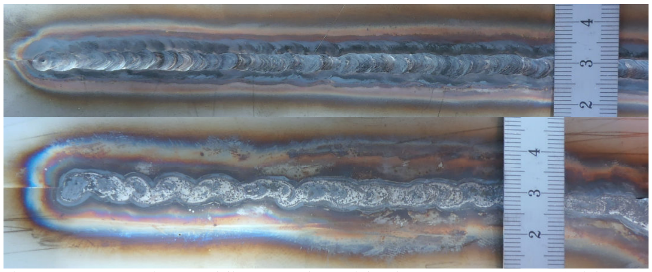


Fig. 2. Interactive welding results with the KUKA LWR (without disturbance). Welding of the professional subject P1 (above), welding of the novice subject N4 (below).

Due to the abrupt position change generated by the disturbance, large forces occur in between the human hand and the torch, observed as the sensor force (f_s). The external force applied on the human hand (f_e) can be captured by simply subtracting the nominal force required for welding (sensor reading just before the disturbance, $f_s(t_d)$) from the sensor reading during the disturbance (5). Moreover, the position change due to disturbance (p_d) can also be captured by subtracting the nominal position (position just before the disturbance, $p_r(t_d)$) from the position during the disturbance (6). In this work we measure the position of the human hand with the position reading of the robot for its end-effector (p_h=p_r); because the subject is constantly holding the torch throughout the experiment. The KUKA LWR has ±0.05 mm repeatability; therefore, we can assume that we have precise enough measurements for the purposes of this study.

$$f_a(t) = \begin{cases} 0, & t \le t_d \\ \neq 0, & t_d < t \le t_e \end{cases} \tag{4}$$

$$f_e(t) = f_s(t) - f_s(t_d), \quad t_d < t \le t_w \tag{5}$$

$$p_d(t) = p_r(t) - p_r(t_d), \quad t_d < t \le t_w \tag{6}$$

In Fig. 3(a, b), the force and position signals are shown respectively for the whole period of one welding session with disturbance (~110 sec). In the force graph we can see the peaks due to the external artificial force. In Fig.3 (d, e) we zoom in the external force and position values in the vicinity of the first disturbance. The artificial force applied at this instant is shown in Fig. 3(c). We observe that within the window of 100 ms before the disturbance, the force remains less than 0.36 N. With the disturbance, in –*x* direction, the force level increases up to 3.4 N. Similarly while the position level before the disturbance remains less than 0.2 mm in –*x* direction, after the disturbance it rises up to 2 mm at 100 ms and more than 3.5 mm afterwards. This is an indication that the external force is much larger than the residual variations of the nominal force required for welding. Therefore, we can use this period after the disturbance to measure the passive dynamics of the holding hand.

A. Measure of Resistance to Disturbance

Impedance is a measure of resistance to disturbances. This resistance is mostly modeled as the mechanical response of a mass, damper, spring system. However, before modeling the reaction in these terms, it is possible to suggest an intuitive measure by looking at the amount of position deviation

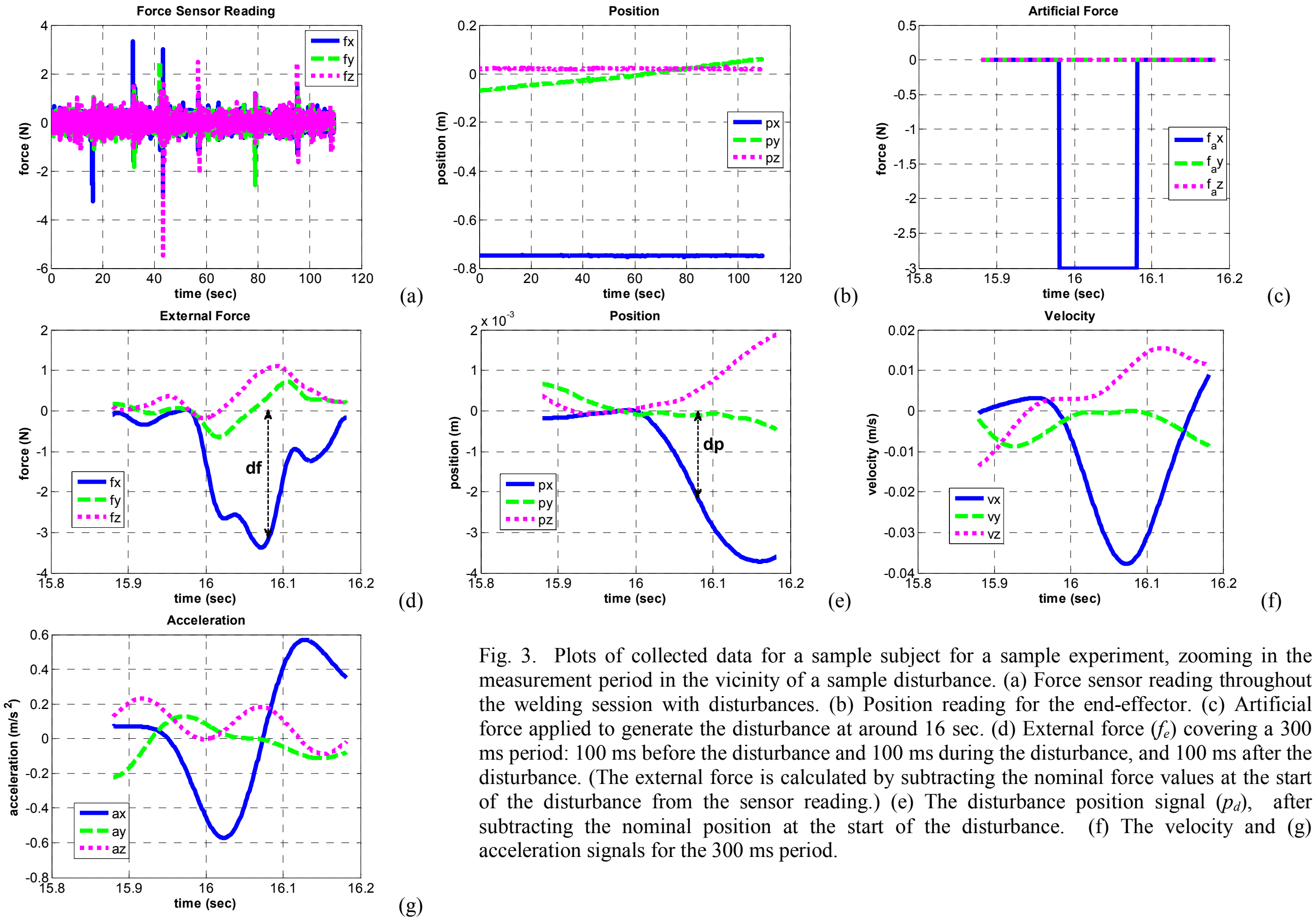


Fig. 3. Plots of collected data for a sample subject for a sample experiment, zooming in the measurement period in the vicinity of a sample disturbance. (a) Force sensor reading throughout the welding session with disturbances. (b) Position reading for the end-effector. (c) Artificial force applied to generate the disturbance at around 16 sec. (d) External force (f_e) covering a 300 ms period: 100 ms before the disturbance and 100 ms during the disturbance, and 100 ms after the disturbance. (The external force is calculated by subtracting the nominal force values at the start of the disturbance from the sensor reading.) (e) The disturbance position signal (p_d), after subtracting the nominal position at the start of the disturbance. (f) The velocity and (g) acceleration signals for the 300 ms period.

when the overall artificial force is applied. In this subsection we simply measure the ratio of the value of the force (df) to the value of position (dp) at the end of the disturbance period (100 ms) (Fig.3 (d, e)). This ratio is named as the ‘resistance’ and designated with r in (7) and in Table II.

$$r = \frac{df}{dp} \qquad (7)$$

In Table II, first we present the results of resistance measurements for all subjects, in x, y, and z directions. For both professionals and novices, the resistance in the x direction is the largest, followed by that in the y direction, and that in the z direction is the smallest. This observation resonates with the previous result that the variance of position in the x direction is the smallest, followed by that in the y direction, and that in the z direction is the largest (Table I). We observe that, for the direction x, the resistance for each professional is larger than that of all novices. We do not observe any significant difference for the resistance in y and z directions. In the rest of the paper, we investigate how these resistances can be distributed as impacts of mass, damping, and stiffness, according to our impedance model.

B. Modeling the Impedance

The impedance we want to measure describes the relation between the series of data collected for the external force (f_e), and the disturbance position (p_d).

The impedance associated with whether the human arm joints or human hand end-point is generally modeled as a mass/inertia, damper, and spring system. Identifying the mass, damping, and stiffness parameters together in a consistent way is mostly performed by using long duration data, such as 300 ms [20], 370 ms [24], 30 sec [10, 13], and 1 minute [15]. In our work we aim at estimating the impedance values using a time window of 200 ms. There are two reasons for the choice of such a shorter duration.

The first reason is related to the voluntary reaction time of human to an external disturbance. The short-latency reflexes take place within the first 25-45 ms after the disturbance; the long-latency reflexes occur within the 45-100 ms period [25]. These are both involuntary movements that can be modeled as a passive dynamical system. After 100 ms, the subject produces voluntarily movements, which can no longer be modeled as a passive system [24]. Therefore the impedance measured in 100 ms might significantly differ from the one measured during a long period lasting several seconds. In our case, we used 200 ms instead of 100 ms, because this was the shortest possible duration that we could determine positive impedance parameters with a rate higher than 90% of the total number of measurements. We assume that for impedance measurement purposes, the impact of voluntary movements in between the 100 and 200 ms period are negligible compared to the passive impedance reaction. This assumption is partially supported by physiology studies of arm reaction with visual feedback. In [26], the average

EMG onset latency of the arm muscles are around 200 ms; in [27] the mean reaction time is determined to be 579 ms for a pulling action.

The second reason for limiting the measurement window to 200 ms is that in a real world task like welding, the external disturbance should be as brief as possible in order to minimally disturb the performance. If we applied long duration disturbances, like for a few seconds, the subject would be totally distracted and would not be able to recover the normal pace of the performance in a short time. Moreover, the uncontrolled movement of the torch for such a long time would totally destroy the regularity of the welding: the melted part on the plate would cool down and it would be necessary to melt it again and again after each disturbance, as it requires at every start of welding.

Our attempts to determine the impedance parameters with only the 100 ms long data failed. This was because the variation of the force/position data in the 100 ms duration was so limited that the parameter estimation problem happened to be indeterminate. Various inconsistent and some negative mass, damping, and stiffness values could fit to the force-position relation. The rate of success to find positive impedance values with our model (8) with 100 ms duration was only 18%. This rate increased to 80% with 180 ms and finally to 98% with 200 ms duration. The impedance values changed with longer durations and after some time became mostly negative, indicating that voluntary reactions became dominant. With 1 sec long duration the rate of success to find positive impedance values was 52%.

The end-point impedance parameters in three Cartesian directions are usually modeled to be coupled, in the form of mass, damping, and stiffness matrices, rather than parameters [12, 28, 29, 10, 11, 30]. In all these work, the movement is restricted to a horizontal plane; therefore the mass, damping, and stiffness matrices are two by two. The minimum disturbance period among those is 0.28 seconds [12]; the others range from 0.3 [29], to 0.45 [28], to 30 [10] seconds. In our case, the movement is in three dimensions. This means that if we modeled the impedance parameters in a coupled way we would have more than the double of the parameters in the mentioned studies, and therefore would need longer duration for estimation. Indeed, when we used the coupled model with duration of 1 sec, we found positive impedance values comparable to those in [28], with a rate of 72%. However, this was a too long duration that voluntary reactions might have blurred the passive impedance characteristics. When we used the duration of 100 or 200 ms with the coupled model, the indeterminacy became so severe that we could hardly ever find positive impedance values (6% and 16% success rate for 100 and 200 ms, respectively).

Perhaps, due to similar difficulties as we faced, coupling effects were ignored in some other studies [20, 15, 31, 16, 18]. Following these, in this study, we model the end-point impedance as a mass, damper, spring system in each of the three main directions, decoupled from each other (8).

$$f_h = (M + m_a)\ddot{p}_h + D\dot{p}_h + Kp_h \tag{8}$$

In (8), M, D, and K are the end-point mass, damping and stiffness values of the human hand for the given direction, and m_a is the mass of the welding torch (300 g). Given the force (f_h), acceleration ($\ddot{p}_h$), velocity ($\dot{p}_h$), and position (p_h) data this equation can easily be solved for the mass, damping and stiffness values by least-squares method (using the pseudo-inverse of the matrix constituted by the acceleration, damping, and stiffness data samples). In our solutions, we used all the data samples collected at 1 kHz rate for each of the 200 ms duration measurements. In total we performed 108 measurements; only 3 of them resulted in non realistic values (negative mass, stiffness, or damping), which we ignored in our results. This means that with 200 ms period the rate of failure in measurements was less than 3%.

Fig.4 (a, b) show a sample measurement. The impedance values found are used to estimate the force and position signals. The position estimate is constructed by solving the second order differential equation in (8) for the position, using the given force data with the determined impedance parameters. The force estimate is constructed by direct calculation (8) with the given position, velocity, acceleration data and the impedance parameters. The estimated trajectories are shown in Fig. 4 with green (light) dashed lines. The measured mass, damping, stiffness values are indicated in the caption of the figure.

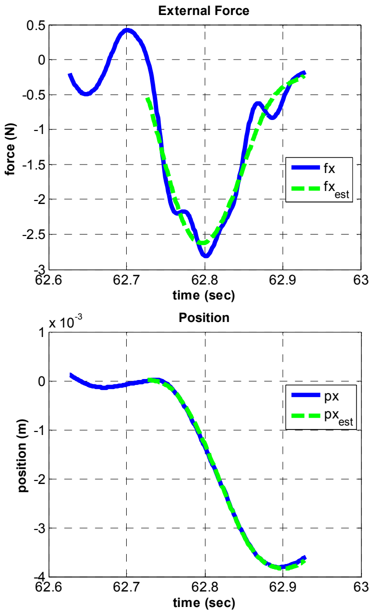
V. RESULTS OF MEASUREMENTS WITH SUBJECTS

In Table II we present the results of measurements for the average end-point impedance parameters for each of the three professional and six novice welders.

The professional welders have larger mass values than the novices in the *x* direction, perpendicular to the welding line. This is not surprising, because, due to their daily manual work, the professional welders have more muscled and heavier arms. However, we do not observe larger mass values in *y* and *z* directions for the professional welders. This is an indication that the larger mass values of professional welders in *x* direction are not only due to the larger masses of their arms, but also due to that the professional welders orient their arms to apply larger resistance in this direction.

The average damping values for the professionals and novices are close to each other in *x* and *z* directions. However, the damping values of the professionals in *y* direction are in general larger than those of the novices. Having larger damping along the welding line is perhaps influential to have more stable speed and hence more regular melting of the metal.

Among the professionals we observe two different distributions of stiffness and damping in *x* direction. For P1 and P2, we observe significantly large stiffness with an average of 768 N/m and moderate damping with an average of 44 Ns/m. For P3, we observe the lowest stiffness over all the subjects, 137 N/m, with the largest damping, 63 Ns/m. The mass value of P3 is also less than the mass value of the other two professionals. It is interesting to observe that although these three professionals demonstrate similar level



(a)

(b)

Fig. 4. Sample force and position signals in the direction of disturbance (x) used for impedance measurement. The force and position signals are re-estimated with the found impedance values; they are shown with the green (light) dashed curves. Measured impedance values for this sample: M=1.8 kg; D=45.3 Ns/m; K=354 N/m.

TABLE II
RESISTANCE (R) AND IMPEDANCE (MASS (M), DAMPING (D), STIFFNESS (K)) VALUES FOR EACH PROFESSIONAL AND NOVICE SUBJECT

Professionals					Novices				
	r **N/m**	*M* *kg*	*D* *Ns/m*	*K* *N/m*		**r** **N/m**	*M* *kg*	*D* *Ns/m*	*K* *N/m*
x direction *(perpendicular to the welding line)*									
P1	*1501*	4.1	45	815	**N1**	*1204*	2.5	34	507
P2	*1812*	4.0	43	722	**N2**	*1005*	1.9	26	589
P3	*1409*	2.5	63	137	**N3**	*1317*	2.3	46	628
					N4	*1037*	1.6	41	360
					N5	*961*	1.6	36	351
					N6	*1091*	0.6	53	414
Average	***1574***	**3.5**	**50**	**558**	*Average*	***1102***	**1.7**	**39**	**475**
Std.dev.	*211*	0.9	11	368	*Std.dev.*	*134*	0.7	10	118
y direction *(along the welding line)*									
P1	*773*	0.1	21	227	**N1**	*823*	0.6	19	110
P2	*683*	0.2	18	201	**N2**	*741*	0.5	15	304
P3	*810*	0.3	24	175	**N3**	*758*	0.5	14	223
					N4	*704*	0.8	11	167
					N5	*779*	1.1	9	244
					N6	*1026*	0.6	11	530
Average	***756***	**0.2**	**21**	**201**	*Average*	***805***	**0.7**	**13**	**263**
Std.dev.	*66*	0.1	3	26	*Std.dev.*	*115*	0.2	4	147
z direction *(along the direction of gravity)*									
P1	*721*	0.5	19	243	**N1**	*725*	0.7	14	151
P2	*723*	0.6	17	232	**N2**	*685*	0.5	12	341
P3	*547*	0.5	19	121	**N3**	*652*	0.7	19	160
					N4	*500*	0.4	18	102
					N5	*604*	0.5	20	102
					N6	*845*	0.3	32	198
Average	***664***	**0.5**	**18**	**199**	*Average*	***669***	**0.5**	**19**	**176**
Std.dev.	*101*	0.1	1	67	*Std.dev.*	*116*	0.2	7	89

of resistance in x direction, the distribution of this resistance takes two different forms: large mass and large stiffness with P1 and P2 and large damping with P3. In y and z directions we observe no significant difference in stiffness between the professionals and novices.

The value of mass is configuration dependent, not controlled by voluntary action. The value of damping is most of the time assumed to be dependent on the muscle activation, but there is no indication that damping can consciously be controlled by the subject. In some studies, it is modeled to be proportional or non-linearly dependent on stiffness [32]. Stiffness, on the other hand is directly related to muscle activation. It is the only one that can consciously be manipulated, therefore it is most interesting from the point of view of understanding "what is to be done" in order to have a good performance. In this respect, the observation of large stiffness with two of the professionals, P1 and P2, is remarkable. The stiffness values in different studies vary due to differences in the methods and arm orientations required for the experimented task. In [9], the stiffness values change in the range 150-700 N/m, in [12] in the range 100-400 N/m along the principal axis, and in [20] in the range 75-264 N/m. In [28] the coupled stiffness values range between 22-448 N/m. In [15] the serially acting hand-tissue stiffness and arm stiffness change respectively in the range 428-868 and 93-355 N/m. The stiffness values we found are comparable to these values. For two of the professionals, P1 and P3, the stiffness in the x direction is slightly larger than those found in these literatures. This is most probably because in our case, the task required larger resistance specifically in the x direction for better performance and these two professionals did it with increasing the stiffness. In [9], the stiffness along the perpendicular direction to the movement is shown to increase from an average value of around 300 N/m in nominal conditions to an average value of around 700 N/m under the condition of an opposing artificial force field. Therefore large values are not surprising under specific cases of tasks. Such larger values as we found for the two professionals (722, 815 N/m), for the x direction, might be effective to have better performance. Our mass and damping values as well compare to those in other studies [20, 28, 15].

VI. CONCLUSION

In this study we present hand impedance measurements of three professional and six novice welders while performing TIG welding interactively with the KUKA LWR robot. In contrast to many others, this study focuses on a real-world manipulation task which requires significant concentration and eye-hand coordination. In agreement with other studies, we found the largest impedance values in the longitudinal direction that the subject faced and that most influenced the quality of welding.

Inspired from our previous work [5], we measured the quality of the performance by means of variation of the torch position. According to this measure we observed that the professionals in average perform better than the novices also with the interactive welding as they do with normal welding without robot. Our results show that in comparison to the novices, the three professionals demonstrate larger resistance in the perpendicular direction to the welding line. Two of the professionals generate the resistance by applying larger stiffness and one of them by applying larger damping.

This study should be considered as a first step to use impedance measurements towards identifying manual welding skills. Perhaps, impedance values are not direct indicators of manipulation skills. Perhaps for many other tasks, the ability to dynamically adapt the impedance is more relevant than having a specific level of impedance. However, for the case of welding, where the interaction does not change much and where the motion requires regularity, we see a tendency of lager impedance with the three professional subjects, in the form of either a larger stiffness or larger damping. This observation suggests that larger impedance might be a part of skilled welding or a factor that might increase the quality of performance. We should note that the present study does not provide enough evidence to generalize this observation to all professional welders; because the number of participants is not enough to provide statistical significance. However, it clearly shows that the three professionals in the study demonstrate characteristically different impedance levels than all the novice subjects and that their way of performance leads to better quality welding. We believe that this observation is important from assistive robotics point of view. The results suggest that a robot might be controlled to provide larger impedance in specific directions (perpendicular to the welding line) in order to assist novice welders. The same principle might apply to other real-world tasks, such as painting, which require regularity of the motion, rather than fast changing interaction forces. Future work will focus on exploiting the results of this study for robotic assistance.

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