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Manual Welding with Robotic Assistance Compared to Conventional Manual Welding

Mustafa Suphi Erden, *Member*

Abstract— **This paper demonstrates the effectiveness of impedance compensation type robotic assistance, presented in a previous work, by comparing manual welding with robotic assistance to conventional manual welding without a robot. The novelty of the current paper is comparison of two sets of data that were published in separate studies, but were not yet compared to each other. One of these previous studies had demonstrated the effectiveness of the robotic assistance in comparison to welding with the robot interactively while the assistance-scheme was off, but not to the case of conventional manual welding as applied every-day in workshops without a robot. The other previous work had collecting welding data with a motion capture system while conventional manual welding in order to demonstrate the differences between novice and professional welders. The comparison presented in the current paper demonstrates that the robotic assistance significantly improves the performance of novice welders in comparison to conventional welding without a robot, whereas the performance of the professional welders remains almost constant across conventional welding and with robotic assistance. The results of this paper show the effectiveness of physically interactive robotic assistance technology to improve the performance of novice welders in the every-day industrial task of manual welding.**

I. Introduction

THIS study demonstrates the effectiveness of a recently developed robotic assistance system for manual welding by comparing the results of welding with the robotic assistance to the conventional manual welding as experienced every day in workshops without a robot. The robotic assistance provides hand-impedance compensation; in other words, it provides an extra resistance to position deviations in the form of a virtual spring, damper, mass system. It was introduced in a recent paper [1]. The current paper very briefly describes the impedance compensation type robotic assistance and then focuses on the comparison of the results of the performance measure for welding with robotic assistance and for conventional welding without a robot, across novice and professional welders.

In [1], the scheme of robotic assistance by impedance compensation was inspired by the hand-impedance measurements across professional and novice welders [2, 3, 4], implemented for manual welding, experimented with novice and professional subjects, and its effectiveness was demonstrated to ameliorate the performance of the novice welders with both quantitative measures and a subjective questionnaire. However, that study compared the performance of welding with robotic assistance to the case of welding with the robot without the assistance, while the robot passively followed human hand movements. In other words, the performance with the robotic assistance was not quantitatively compared to actual conventional manual welding as exercised in workshops without a robot. In this paper the data collected during welding with robotic assistance at EPFL [1] and the data collected during conventional manual welding without a robot at TU Delft [5, 6] are compared. In both cases the data was collected from novice and professional welders. The reader is referred to these papers for the references, background information, and the details of impedance compensation type robotic assistance.

Section II introduces the experimental setups used to collect data while welding conventionally and with robotic assistance. This section also introduces the performance measure used to compare the welding under the two conditions. In Section III a summary of the robotic assistance scheme by impedance compensation is given. Section IV presents the quantitative results of the comparison of welding conventionally and with robotic assistance, across novice and professional welders. Section V concludes the paper.

II. Experiments and Performance Measure

For the case of conventional manual welding without assistance, the data from the previous study [5, 6] are used. The data of torch-tip position were collected with an infrared motion capture system while 4 professional and 14 novice welders did TIG welding without external feed [Fig. 1(a)]. The TIG Welding setup was a standard one that can be found in most mechanical workshops.

For the case of welding with robotic assistance, the data from the previous study [1] is used. In that work, the subjects used the interactive robotic manual welding system shown in Fig. 1(b) and again did TIG welding without external feed. The interactive manual welding system composed of the KUKA LWR 4+ robot, an ATI force sensor attached to its end-effector, and a standard TIG Welding setup. The robot joint-angle readings provided the torch-tip

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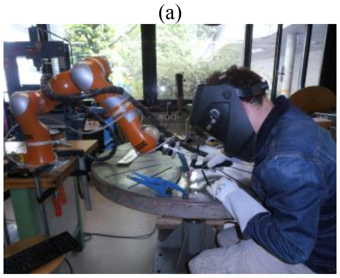
This paper uses the results of the experiments that were conducted partly at Delft University of Technology (TU Delft), The Netherlands, and partly at École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, when the author was a post-doc researcher in each place. The research at École Polytechnique Fédérale de Lausanne was funded by the Marie Curie Intra-European Fellowship of the author: SkillAssist, PIEF-GA-2011-297857.

(a)



(b)

Fig. 1. (a) Setup used for data collection in the study [5, 6] while professional and novice welders did conventional manual welding without a robot. The indicated three markers provide the tip point position of the welding torch. (b) Interactive manual welding with robotic assistance applied in [1]. The robot joint-angle readings provide the position of the tip point of the welding torch.

position used in the analyses. The robot was admittance controlled through the force sensor. For assistance, the robot applied artificially constructed virtual forces in the form of a virtual mass, damping, and spring in the directions perpendicular to the direction of welding. There was no pre-programmed welding direction; it was decided by the welder in the run-time and estimated by the robot in real-time. Please see [1] for the details.

In both studies, while welding conventionally and with robotic assistance, the subjects were left free to choose their arm and body orientation, as they felt most comfortable and most effective. They were instructed to aim at their best performance. During welding with robotic assistance [1], the subjects welded 1.5 mm thick stainless steel plates. They used 40 Amperes DC current. During welding without the robot [5, 6] the subjects welded 4 mm stainless steel plates with 80 A. Thick plates are usually welded slower; however, in these experiments inter-subject differences had a larger impact on the difference of welding speed compared to the impact of different plate thickness across the two experiments. This is because the subjects varied a lot in maintaining a close distance between the torch-tip and the metal plate, which enormously impacted the melting speed/amount and consequently the welding speed.

The comparison of performance in this study is based on the measure of variance in the position of the tip of the welding torch. The variation of the torch-tip position is an indicator of the hand-tremor of the subject and is closely related to the quality of the weld. There is less hand-tremor with more skilled subjects. In order to measure the impact of the hand-tremor, it is necessary to filter out the slow variations due to the intentional control of the welding torch, i.e. intentional control of the welding speed due to the aforementioned reasons and intentional control of the welding path. The subjects followed a real-time decided and dynamically changing curved path above the welding line in order to (*i*) balance the melting on each side of the metal junction [Fig. 2(a)] and (*ii*) accommodate the deformation of the metal during welding by increasing the height of the torch-tip from the plates [Fig. 2(b)]. The slow variations are filtered out by passing the position signal through a high pass filter with 0.1 Hz cutoff frequency (fourth order Butterworth filter). After eliminating the slow variations, the signal contains only the high-frequency components of position change, which correspond to the impact of hand-tremor while welding. In this study the performance measure focuses on the impact of the hand-tremor in all three Cartesian directions.

Following the approach in [1] the performance is measured as follows: After high-pass filtering the position signals (1), the variance of the three components of the position signal is computed (2). Besides, the *variation* of the magnitude of the position is computed as in (1-3), where p_{if} stands for the filtered i^{th} component of the position signal, r for the reconstructed magnitude after filtering the signals, and v for the value of variation.

$$p_{if} = \text{high\_pass\_filter}(p_i, 0.1\ Hz) \tag{1}$$

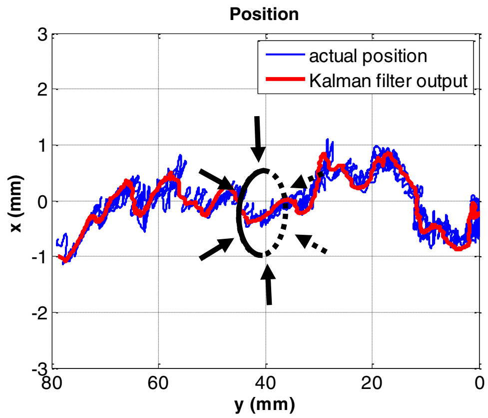
$$\left.\begin{aligned} \text{var}(x) &= \text{var}(p_{xf}) \\ \text{var}(y) &= \text{var}(p_{yf}) \\ \text{var}(z) &= \text{var}(p_{zf}) \end{aligned}\right\} \tag{2}$$

$$v = \text{var}(x) + \text{var}(y) + \text{var}(z) \tag{3}$$

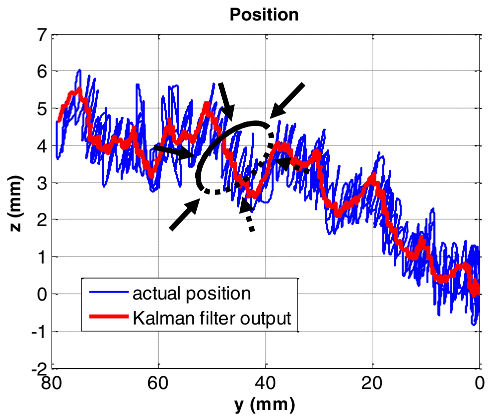
III. ROBOTIC ASSISTANCE WITH IMPEDANCE COMPENSATION

The impedance compensation type robotic assistance is based on applying external impedance in all directions within the plane perpendicular to the estimated direction of hand movement. Technical details of this robotic assistance can be found in [1]. Here will be given a brief description of how the impedance compensation suppresses hand-tremor and helps to have smoother tool movements.

Fig. 2 shows a typical manual welding data (tool-tip position data, blue scattered line) for welding approximately along the line *x*=0 and the estimate of the intended path by the welder (red smooth line), which is plotted on top of the welding data. This estimation is produced in real-time by passing the actual tool-tip position data through a Kalman filter [1]. Please note in Fig. 2(a) that the welder intentionally follows a curved path in order to balance the melting of the metals in the two sides of the welding line. The estimation is successful to catch this real-time change of the path. The actual welding line gets curved also in the vertical plane due to metal deformation; therefore, as the change in the level of the height of the torch-tip (*z* values) in Fig. 2(b) indicates, the welding path is not anymore in a horizontal plane. We observe in Fig. 2 that the Kalman filter successfully estimates the intended 3D welding path constantly changing above the metal plates.



(a)



(b)

Fig. 2. A typical manual welding data (blue scattered line) for welding approximately through the line x=0 and z=2, shown in (a) x-y and (b) y-z planes. The welding path gets curved due to metal deformation throughout welding therefore the welding line is not anymore on the x-y plane, as the change in the level of the height of the torch-tip (z values) indicates. The line z=0 shows the level of the torch tip at the starting point, which is approximately 2 mm above the metal plates. The Kalman filter output (red smooth line) is plotted on top of the welding data. The arrows indicate the desired impedance compensation to be performed by the robot in all directions within the plane perpendicular to the instantaneous welding direction (hence perpendicular to the plane of the paper: the dots are intended to give a feeling of depth).

The arrows in these figures indicate the desired impedance compensation to be performed by the robot in all directions within the plane perpendicular to the instantaneous welding direction. The overall assistive force ($\boldsymbol{f_a}$) corresponds to the sum of the virtual stiffness, damping, and mass related impedance compensation forces ($\boldsymbol{f_s}$, $\boldsymbol{f_d}$, $\boldsymbol{f_m}$), all artificially generated and integrated with the admittance control scheme (4). Please see [1] for the details of how these virtual impedance forces are generated.

$$\boldsymbol{f_a} = \boldsymbol{f_s} + \boldsymbol{f_d} + \boldsymbol{f_m} \quad (4)$$

Due to the assistive force, the tremor around the intended path is suppressed and the subject is able to perform much smoother welding path. The decrease in the amount of these tremor movements with robotic assistance in comparison to those with the conventional manual welding is the focus of the following analysis. The amount of hand-tremor is measured in terms of the variance of the tool-tip position, after eliminating the intended variations by passing the signal through a high-pass filter, as explained in the previous section.

IV. Results of Performance Measures with Conventional Manual Welding and Welding with Robotic Assistance

Table I presents the mean variance and variation values for the professional and novice welders while they welded conventionally without a robot [5, 6] and with robotic assistance [1]. Fig. 3 depicts these values in the form of a bar graph.

Following the method in [1], the impact of three factors was analyzed on the variance (x, y, z) and variation (v) measures: *mode* of welding (conventional welding/welding with robotic assistance), *expertise* (professional/novice), and *direction* (x/y/z/v). A log transform was applied to all variance and variation data in order to achieve a normalized distribution in each of the 16 compared groups. Each of the 16 groups passed the Lilliefors normality test. A three-way ANOVA test (*anovan()* in Matlab) was run over the data. Finally a post hoc analysis was performed using Tukey's least significant difference procedure (*multcompare()*) to find the groups that significantly differed from each other with respect to any factor. In all tests the threshold (maximum) $p=0.05$ was used for statistical significance.

The three-way ANOVA found significant effect due to the factors *mode* [*degrees of freedom (d)=1; F statistics (F)= 9.52; p value for the F statistics (p)<0.003; effect size* $(\eta^2)=0.013$], *expertise* ($d=1$; $F=110.10$; $p<0.001$; $\eta^2=0.150$), and *direction* ($d=3$; $F=127070$; $p<0.001$; $\eta^2=0.520$). A significant interaction was found between the factors mode and expertise ($d=1$; $F=8.25$; $p<0.005$; $\eta^2=0.011$), and no significant interaction was found between the factor direction and the other two factors ($p=0.577$ and $p=0.954$, respectively for mode and expertise). The results of the ANOVA test confirm the previous findings that the expertise and direction of welding are significant factors in measure of variance [2]; and further indicate that the robotic assistance makes a significant impact depending on whether the subject is a novice or professional welder.

The post-hoc analysis identified the groups which differed significantly with $p<0.05$. The groups that are interesting from comparison point of view and had a statistically significant difference are indicated with an asterisk in Table I. We observe that when they welded conventionally (without a robot) there is highly significant difference between the professional and novice welders in the variances (in all three directions) and variation with p values all lover than *0.0001*. With the robotic assistance, we observe that the significance in difference decreases and even disappears for the direction z, suggesting that the difference between the novice and professional welders has been decreased due to the robotic assistance. In all cases, the mean value of the professional welders is lower than that of the novice welders, indicating less hand-tremor with the professional welders.

We observe a significant difference in the variance of novice welders in all directions except for z, when they welded conventionally and with robotic assistance. The

TABLE I

MEAN VARIANCE OF POSITION FOR PROFESSIONAL AND NOVICE WELDERS WHILE THEY WELDED CONVENTIONALLY AND WITH ROBOTIC ASSISTANCE*

	Novice Welders				*Professional Welders*			
	variance (filtered, 0.1 Hz) (mm^2)			variation	variance (filtered, 0.1 Hz) (mm^2)			variation
	var(x)	*var(y)*	*var(z)*	*v*	*var(x)*	*var(y)*	*var(z)*	*v*
Conventional Welding [5, 6]	0.32 ±0.09	1.31 ±1.08	0.57 ±0.20	2.19 ±1.13	0.13 ±0.07	0.52 ±0.41	0.22 ±0.09	0.87 ±0.47
Welding with Robotic Assistance [1]	0.23 ±0.10	0.71 ±0.27	0.41 ±0.19	1.35 ±0.48	0.12 ±0.04	0.39 ±0.23	0.29 ±0.16	0.81 ±0.34
Decrease	0.09*	0.60*	0.16	0.84*	0.01	0.13	-0.07	0.06
p value	*0.0497*	*0.0115*	*0.0572*	*0.0144*	*0.9809*	*0.3240*	*0.3141*	*0.7771*

Conventional Welding, novice vs. professional: *var(x)* * *p<0.0001*; *var(y)* * *p<0.0001*; *var(z)* * *p<0.0001*; *v* * *p<0.0001*

Welding with Robotic Assistance, novice vs. professional: *var(x)* * *p<0.0084*; *var(y)* * *p<0.0036*; *var(z)* *p<0.0756*; *v* * *p<0.0164*

*The comparisons indicated with (*) are found to be significantly different by the post-hoc analysis following a three-way ANOVA with significance level *p<0.05*.

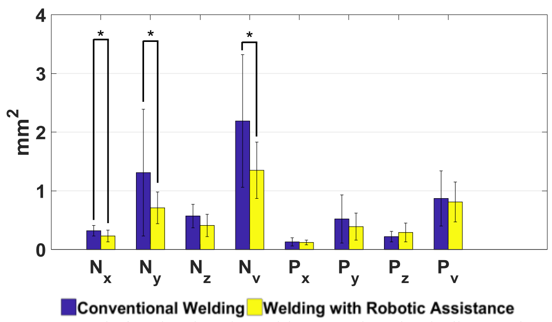


Fig. 3. Bar graph for the data in Table I. Dark color indicates the data for conventional welding without a robot. Light color indicates the data for welding with robotic assistance. N_x, N_y, N_z, N_v indicate the average novice subject variance of position in the directions *x*, *y*, *z*, and the average position variation, respectively. Similarly, P_x, P_y, P_z, P_v indicate the corresponding for the professional subject.

mean of variance with robotic assistance is significantly less than that of the conventional welding. The amount of decrease with robotic assistance is 0.09 ($p=0.0497$), 0.60 ($p=0.0115$), 0.16 ($p=0.0572$), and 0.84 ($p=0.0144$) mm^2, for *x*, *y*, and *z* directions and for variation, respectively. We do not observe any significant difference between the variance and variation of professional welders when they welded conventionally and with robotic assistance (*p* values for *x*, *y*, and *z* directions and variation are *0.9809*, *0.3240*, *0.3141*, and *0.7771*, respectively). These observations indicate that robotic assistance makes a significant impact on the performance of the novice welders but no significant impact, either positive or negative, on professional welders.

V. CONCLUSION

In this paper, the effectiveness of the impedance compensation type robotic assistance for manual welding is demonstrated by comparing the data of welding with robotic assistance to the data of conventional welding without a robot, across professional and novice welders. The results show that the robotic assistance improves the manual welding of the novice subjects by suppressing their hand-tremor. The performance of the professional welders did not improve to a significant degree. This is understandable, because professional welders already weld almost perfectly and do not demonstrate much hand-tremor during conventional welding. It is important to note here that, the robotic assistance did not disturb the performance of the professional welders in comparison to conventional welding. Improving the performance of the novice subjects and not disturbing that of the professional subjects demonstrates the practical usefulness of the robotic assistance for the industrial task of manual welding. The results of this paper provide evidence for the benefits of bringing robotic assistance technologies out from the labs to the actual industrial environment.

The performance measure used in this study focused on the ability to manipulate the hand in a stable way with minimum tremor. This criterion does not take into account the actual quality of the weld on the metal, which can be assessed by measuring the depth of weld bead and by a strength test. The quality of weld relates not only to the stability of hand manipulation but also to the knowledge about the appearance of the molted metal throughout welding. Since the novice welders do not have such knowledge, testing of the weld quality was not relevant in this study. However, this might be relevant and informative to compare across the performance of professional welders while welding conventionally and with robotic assistance.

REFERENCES

[1] Erden, M.S. and Billard, A., "Robotic Assistance by Impedance Compensation for Hand Movements While Manual Welding", *IEEE Transaction on Cybernetics*, 46 (11): 2459-2472, 2016.

[2] Erden, M.S., Billard, A., "Hand Impedance Measurements during Interactive Manual Welding with a Robot", *IEEE Transactions on Robotics*, 31 (1): 168-179, 2015.

[3] Erden, M.S., Billard, A., "End-point Impedance Measurements at Human Hand during Interactive Manual Welding with Robot", *Proc. of IEEE International Conference on Robotics and Automation (ICRA 2014)*, May 31 - June 7, 2014 Hong Kong, China, pp. 126-133, 2014.

[4] Erden, M.S. and Billard, A., "End-point Impedance Measurements across Dominant and Non-Dominant Hands and Robotic Assistance with Directional Damping", *IEEE Transactions on Cybernetics*, 45(6):1146-1157, 2014.

[5] Erden, M.S. and Tomiyama, T., "Identifying welding skills for training and assistance with robot", *Science and Technology of Welding and Joining*, vol. 14, no. 6, pp. 523-532, 2009.

[6] Van Essen, J., van der Jagt, M., Troll, N., Wanders, M., Erden, M.S., van Beek, T., and Tomiyama, T. (2008), "Identifying the welding skills". *Proc. of the IEEE/ASME Int. Conf. on Mechatronic and Embedded Systems and Applications*, Beijing, pp. 437-442.