Robot Assistance for Manual Welding
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MASTER OF SCIENCE THESIS
Robot Assistance for Manual Welding

ME-BME-BMD-IMS
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October 19, 2009

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Preface

This is my Msc. thesis for which the research was done from January to October 2009. It is a continuation of my literature study “Using Human Machine Collaboration to Improve Welding”. This research is the first step in the development of the research topic, “Physical Human Robot Interaction”, of my direct supervisor, Mustafa Suphi Erden. I want to take this opportunity to thank him for his support and research suggestions during this period. Also, I would like to thank professor Tomiyama for his intellectual support and research suggestions along the way.

In addition, I want to express my gratitude to Thom van Beek for helping with the test set-up. Furthermore, I want to thank Jurriaan van Slingerland for providing information and support with respect to welding.

Finally, I want to thank my sister Stana for suffering through numerous versions of my thesis in order to provide a layperson’s view on the thesis and, of course, improving my spelling and grammar.

Slobodan Marić.

Delft, October 19, 2009
Abstract
In this thesis, manual welding with robot assistance is studied. A variable impedance control scheme is developed to suppress the undesired movements of unskilled welders. The impedance parameters of damping and mass are investigated. Mass increases the undesired movements and is disregarded. Damping decreases the undesired movements, helping to derive an optimum damping value. A variable impedance control scheme is applied to ease the transferring of the torch while not welding. A switch is built that facilitates the movement of the torch between performance and transferring phases. Test results show that with robot assistance an unskilled welder is better able to track the seam, and the welds are straighter and more uniform in width.
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1. Introduction
Welding is widely used in various industries [1, 2, 3]. Although in many industries welding is being automated with the help of robotics, as is happening in the automotive industry, there is still a great need for manual welding. Full automation is not always feasible, because of the complexity and variety of various welding tasks. Also, some companies are small and, therefore, prefer the flexibility of manual welding. Manual welding requires great deal of skill and that is why skilled welders are highly sought by various industries. But skilled welders are becoming more and more scarce and the costs of hiring them are increasing, because of the decreasing popularity of the profession [4, 5, 6]. Manual welding is difficult since it requires a great deal of skill and precision. With assistance from robot, even unskilled welders might be able to weld competently. This might help to alleviate the scarcity of skilled welders.

In this thesis, a new method of robot assistance is developed, which will assist the human with variable impedance control and weight compensation. Impedance control is used to suppress the vibrations of an unskilled welder. Weight compensation is a simpler concept; the robot carries the welding torch and cable.

Variable impedance is used, instead of constant impedance, because there are two different phases in the welding task. First, there is the performance phase, which consists of movements the welder makes during the actual welding. This phase is characterized by slow travel speeds and high precision. Second, there is the transfer phase, which consists of moving and positioning the welding torch so the actual welding can commence. The transfer phase is characterized by faster travel speeds and low precision.
Fig. 1. The two phases. The transfer phase consists of positioning of the torch before the actual welding. The performance phase consists of movements the welder makes during actual welding.

If the impedance parameters are set high, then the robot always behaves as in the performance phase, with slow and accurate movements. This creates a difficulty for the transfer phase. And if the impedance parameters are set low, then the robot always behaves like in the transfer phase with fast movements. In this phase the robot will not provide any assistance to the welder. In this thesis the robot being used for welding assistance is the HapticMaster.
This thesis has the following structure. In section 2 performance criteria of welding skills are determined. The differences between skilled and unskilled welders are used to derive these performance criteria. Section 3 provides an explanation of the HapticMaster and the impedance control. In section 4, we clarify the performance phase. Here the effects of the impedance parameters on welding skills are researched. Hereafter tests are done with the purpose of determining the proper parameters for impedance. These testing procedures require a large number of experiments, and in order to facilitate these procedures, an airbrush is used to emulate actual welding. The transfer phase is discussed in section 5. Velocity data is used to distinguish the performance and the transfer phase. A velocity switch is built that lowers the impedance parameters when a certain velocity is exceeded. An airbrush is also used for this test, for the same reason as mentioned above. In section 6, we carry out the final test which is to use robot assistance for welding. All the data from all of the previous tests is applied in actual welding with a real welding torch. Two welds are made. One with robot assistance and one without robot assistance, which are thereafter visually compared. Finally, in section 7 concluding remarks are given and suggestions for future work are provided.
2. Performance criteria of welding skills
A skilled welder is able to select the correct parameters, adjust them continuously and maintain the correct welding torch position [1]. These three criteria are needed to produce a good quality weld. This thesis is concerned with maintaining the correct position of the welding torch, which requires precision and stability. This is fundamental for a good and constant weld [1].

According to a recent study [7], a skilled welder is better able to maintain the correct welding position, with stability and precision, than an unskilled one. He has less variance in both his movements and travel speed. Furthermore, a distinction is made between desired and undesired movements. Desired movements are movements made in the frequency range of 0-0.1Hz that form the actual welding line. Undesired movements are movements resulting in deviations from this welding line. That study shows that welding skills can be evaluated by looking at the variance of filtered position data. This position data is put through a high pass filter, as a result of which, low frequencies (0-0.1 Hz) are filtered out. Thus, only the frequencies above 0.1 Hz remain, which are the undesired movements. In this thesis the variance of these undesired movements will be used as a performance criterion to determine the welding skills.
Fig. 2. The calculation of the variance of undesired movements. First, position data is filtered with a high pass filter to get rid of the welding line. Hereafter the variance is calculated in all three directions (x, y, z). The average of the three variances is used for evaluating the quality of welding skills.

Fig. 3. Blue represents skilled performance data and purple represents unskilled performance data. Movement in x-direction (in mm) after it has been filtered by a high pass filter with a cut-off frequency of 0.1 Hz. The welding line has a frequency of 0-0.1 Hz and has been filtered out, what remains is undesired movements with a frequency greater than 0.1 Hz. Welding skills are evaluated by checking the variance of undesired movements, the smaller the variance, the better the welding skill. [7]
When comparing welding skills, the lower the variance of undesired movements, the better. By removing the welding line (i.e. desired movements in the frequency range 0-0.1Hz) we can compare the variance of different shape of welds directly, because the undesired movements are not fully dependant on the shape of the welding line. Comparing variance of undesired movements is not the only evaluation criterion. A visual evaluation must be made to ensure the welder has followed the intended trajectory. A welder can miss the trajectory because of other reasons than undesired movements, for example, loss of concentration or poor visual conditions.
3. HapticMaster and Impedance control

The HapticMaster is the robot that is used in this thesis to assist the welder. The HapticMaster is a 3-DoF (x, y and z Cartesian directions) robot that is well suited to work together with a human. The robot is operated by directly manipulating the end effector.

![Diagram of HapticMaster](image)

**Fig. 4. Picture and schematic overview of the HapticMaster**

The user takes hold of the end effector of the HapticMaster. The end effector has a force sensor that measures the user’s force data, which is then sent in a model. This model uses the position and velocity measurements together with the abovementioned force data to control the motors. The motors generate real forces that in turn are used to power gears, worm wheels and all other kinds of transmissions, causing the HapticMaster to move. Sensors are used to measure the position and velocity. These measurements are used in the model. There are various advantages in using this device, the most important advantages being that (i) virtual surfaces and other haptic effects are created, (ii) there is zero friction, and (iii) there is no backlash.
In short, this means that the end effector of the HapticMaster [8] is controlled to have the following impedance characteristics.

\[ F = m \cdot \frac{d^2x}{dt^2} + D \cdot \frac{dx}{dt} + k \cdot (x - x_0) \]

- \( m = \) mass [kg]
- \( D = \) viscous damping factor [N·s/m]
- \( F = \) force applied by the operator [N]
- \( k = \) stiffness [N/m]
- \( x_0 = \) reference position [m]
- \( x = \) position [m]
- \( \frac{dx}{dt} = \) velocity in [m/s]
- \( \frac{d^2x}{dt^2} = \) acceleration [m/s²]

The last term \( k \cdot (x - x_0) \) uses a position change with respect to a reference position. In welding stiffness is not applicable, because stiffness requires a stationary reference point. This means that the force increases the further you are away from the reference point, as if a spring is connected to a torch. This does not happen with a real welding torch; therefore it should not happen in this case either. For this reason we disregard the stiffness term and the impedance control becomes:

\[ F = m \cdot \frac{d^2x}{dt^2} + D \cdot \frac{dx}{dt} \]

The HapticMaster senses with a force sensor the force applied by the human operator. Mass and damping are impedance parameters specified by the programmer/designer. The HapticMaster uses these parameters to calculate the required velocities and accelerations. The two most important parameters are the viscous damping factor and mass, because they change the behaviour of the whole system.
4. Test set-up for the performance phase
In this test the effects of the two impedance parameters, damping and mass, will be investigated. Because these tests are numerous, an airbrush is used to emulate actual welding. The reasons for using an airbrush are explained below and the similarities between using an airbrush and actual welding will be touched upon.

4.1. Emulating Welding
Tuning the parameters is time intensive and it might require multiple tests per subject, therefore it is not practical to do tests with a welding torch. Problems that arise are: (i) multiple tests require great quantities of metal, which is costly, (ii) welding is time intensive and complex, (iii) there is need for protective clothing and (iv) welding takes some preparation time. Because of all the abovementioned problems a tool is used to emulate welding, namely an airbrush. An airbrush uses pressurized air to atomize paint in very tiny droplets, comparable to spray transfer in welding. It is used to provide visual feedback to the user. During actual welding the welder is able to see the molten material providing him visual feedback. This makes it easier to judge what is happening and make corrections, if necessary. If the material is not melted he has to stay on the spot, to heat the material until it melts. If the molten material is not on course, he has to get his welding torch back on course. The same applies with respect to an airbrush. If the line of paint is not on target, the user of the airbrush can act accordingly. Taking the above into account, instead of welding, the test subject will be painting.

*Fig. 5. The airbrush type that will be used for the experiments*
We will connect the airbrush to the HapticMaster with the help of a plastic connection part. This connection part can rotate around its length axis, to allow the airbrush to be used by both left and right handed test subjects.

Fig. 6. The airbrush connected to the HapticMaster

Fig. 7. Close up view of the plastic connector, the plastic connector can be rotated along its length axis
4.2. Similarities between an Airbrush and Welding Torch

The similarities between an airbrush and a welding torch are that in both cases you will have to follow a certain trajectory and minimize undesired movements. The trajectory with an airbrush will be a circle instead of a line. This is to test all directions (x, y and z) all at once. The test subject is asked to colour a circle as accurately as possible. The circle line has a certain width and the goal is to try to fill in the line completely. If the test subject holds the airbrush too close, it will not be possible to colour in the line completely and the colour will be darker. If the airbrush is held too far away, the line will be “overfilled” and the colour will be lighter. Due to the fact that the airbrush paints in a conical fashion, the further away the airbrush is held from the paper the bigger the paint surface becomes.

![Visual representation of the effects of holding the airbrush too close and holding it too far](image)

*Fig. 8. Visual representation of the effects of holding the airbrush too close and holding it too far*
The painting lines will be evaluated in the same way as in actual welding, for the ability to follow the line. The variance of the undesired movements will be calculated. If the variance is lowered, then the quality will improve. There is an advantage in measuring the variance of undesired movements, instead of the whole frequency range. It does not matter what the shape of the painting/welding is. By removing the welding line (frequency 0-0.1 Hz) we can directly compare welds with each other irrespectively of their form. There will also be a visual evaluation. The paint line has to stay within the lines. If the test subject cannot follow the trajectory, there is no point in calculating the variance of undesired movements either.

The goal is to find the effect of various magnitudes of damping and mass with respect to welding skills. We evaluate the welding skills by examining the variance of undesired movements and checking visually if the test subject was able to follow the trajectory. If two tests are done with an airbrush that is connected to the HapticMaster, with the only difference between those tests being that the second test has higher impedance parameters, resulting in a significant drop of the variance of undesired movements, then it can be safely stated that this improvement is caused by the impedance parameters. It also stands to reason that these impedance parameters would also improve actual welding skills, even if the trajectory is of a different shape. To be absolutely sure of this, tests with actual welding will be done afterwards.

4.3. **Experiments to determine mass and damping factor**
To determine what effects mass and damping have on the variance of undesired movements some experiments are run. Each experiment will have multiple test subjects. The test subject is asked to colour a circle as accurately as possible. The subject will paint for 30 seconds before being instructed to stop. This test is done multiple times for various masses and damping factors. Besides the variance of undesired movements, the force and the speed are also measured. By multiplying the force with the speed the power is calculated.
Fig. 9. Visual representation of the experiment that will be run. The subjects start from the starting point and weld for 30 seconds. The endpoint differs for each subject; some paint faster and therefore reach further.

Fig. 10. Test set-up
4.4. Results
Two separate tests are executed. For the first test mass is increased in increments. The increments are 3 kg, 10 kg, 20 kg, 30 kg, 40 kg and 50 kg. The HapticMaster measures the force applied by the human and applies this force to the virtual mass. This HapticMaster then calculates the displacements caused by the human force on the virtual mass. If mass is zero this would mean that the acceleration is infinite. Even small masses would make the HapticMaster move at dangerous speeds. This is why the minimum mass is 2 kg. But this makes the HapticMaster vibrate a lot, therefore 3 kg is used instead. For the second test the mass has remained at 3 kg, but the magnitude of damping has been increased in increments. The increments are 0 N·s/m, 50 N·s/m, 100 N·s/m, 150 N·s/m, 200 N·s/m, 250 N·s/m and 400 N·s/m.

![Graph](image)

Fig. 11. Variance of undesired movements (straight lines) with respect to various masses (3 kg, 10 kg, 20 kg, 30 kg, 40 kg, 50 kg) and the average power (dotted lines) with respect to various masses.
The graph of the mass test is shown in figure 11. The straight lines are the variance of undesired movements and the dotted lines are the power graphs (i.e. force applied by the human multiplied by the velocity of the HapticMaster). The black dotted and straight lines are the average power and variance respectively. It is observed that there is an increase of power and an increase of the variance of undesired movements when mass is increased. The variance does decrease a little at higher masses, but it becomes almost impossible to stay within the trajectory. A large mass creates a large momentum of movement. When there is a deviation from the painting line the test subject reacts to it with a counter force. Because of the large momentum this causes a deviation in the opposite direction. Suppressing these oscillations becomes harder if the mass increases. These oscillations make it impossible to follow the painting line.

![Image](image.png)

*Fig. 12. An example where the subject had trouble controlling a large mass because of the oscillations*

The graphs depicting the effect of damping are shown in figure 13. The straight lines are the variance of the undesired movements and the dotted lines are the power graphs. The black dotted and straight lines are the average power and variance respectively, which are pictured in figure 14. The variance of undesired movements decreases if the magnitude of damping is higher. The power rises steadily with the increase of damping. There is a trade of between power and decrease of variance. Increasing the power will lead to more effort in moving the torch. The strategy is to look at the average variance (figure 14) and pick the lowest factor of damping where
there is no further significant decrease of variance. This corresponds to a damping factor of 100 N•s/m

Fig. 13. Variance of undesired movements (straight lines) with respect to various damping factors (0 N•s/m, 50 N•s/m, 100 N•s/m, 150 N•s/m, 200 N•s/m, 250 N•s/m, 400 N•s/m) and the average power (dotted lines) with respect to various damping factors.
When plotting the x and y components of the airbrush trajectories, it can be observed that damping makes the circle smoother, as can be seen in figure 15.

The impedance parameters are 3 kg for the mass and 100 N·s/m for damping.
5. Test set-up for the transfer phase

Now that the impedance parameters have been chosen a new problem arises. The high damping factor (100 N•s/m) makes it quite difficult to position the airbrush; it makes moving the airbrush to the place where one can start painting tiresome and slow. The movement of the airbrush or a welding torch to a destination place, in order to start the painting/welding, is called the transfer phase. To decrease the difficulty of moving the airbrush variable impedance is used [9, 10, 11]. Variable impedance means that the high impedance parameters, in this case the damping factor, are lowered or completely turned off if a certain velocity, force or acceleration is exceeded. Before a certain form of variable impedance is chosen, some tests are run, to determine the easiest way to distinguish the performance and transfer phase. These tests are the so-called initial tests. After the initial tests are done, the parameters of the variable impedance are chosen. And finally two different kinds of variable impedance are compared to each other and the best one is chosen.

5.1. Initial tests

During this test we will determine the distinctions between the transfer phase and the performance phase. The test subject will be required to paint a quadrant of a circle, then transfer to the circle below and paint a quadrant of that circle. During the transfer phase the test subject is asked to move naturally; the test subject should not rush when moving to paint the next part, nor should he move slowly. This test has therefore three phases, the performance phase, the transfer phase and, again, the performance phase.
Fig. 16. The initial test experiment. The subject starts at starting point 1 and paints the circle until he/she reaches end point 1. Then he transfers to starting point 2 and paints until end point 2 is reached.

Two situations will be compared, one where the impedance parameters are set low (mass 3 kg and damping 0 N•s/m) and another where the impedance parameters are set high (mass 3 kg and damping 100 N•s/m). There are many possible ways to distinguish the performance and the transfer phase. Because the transfer phase takes place at higher speeds, velocity can be used to detect the transfer phase. The HapticMaster measures human force and uses an internal model to calculate the displacements and velocities, so force can be a manner to detect the transfer phase. Also, acceleration can be used to detect the transfer phase; the acceleration would increase at the start of the transfer phase. Hence, during the initial tests we will measure acceleration, velocity and force. The measurements thereof which show the clearest distinction, between performance phase and transfer phase, will be the chosen measurement. However, first the results of the initial tests are set out.
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Fig. 17. Results of the initial test with no damping

Fig. 18. Results of the initial test with full damping
When reviewing the results of the tests with no damping and the test with full
damping, the difference can be immediately seen. It takes the test subject
much more effort to move the airbrush in the situation of full damping than in
the situation of no damping, which is proved by the magnitude of applied
human force as shown in figure 17 and figure 18. These figures also clearly
show that the transfer of the airbrush takes longer in the situation of full
damping. These are the reasons for using variable impedance.

The performance phase and transfer phase are easily distinguished in figure
17 and figure 18. Velocity (blue line) increases at the beginning of the
transfer phase. Thereafter, velocity reaches a maximum and then reduces
until the magnitude of velocity is back to the beginning stage. This means
that the performance phase is reached again. When looking at the human
force (red line), the transfer phase starts with a sudden increase of force. But
because the force has high fluctuations, it is hard to determine where it ends
exactly. The same applies to acceleration (green line). Therefore velocity is
chosen to distinguish the transfer phase and the performance phase.

5.2. Choosing parameters for variable impedance
Up to this point we determined how to distinguish the performance and
transfer phase. To achieve variable impedance, we will build a velocity
switch. One paper [9] discusses the workings of a velocity switch. The paper
is based on a study in which a robot was used to execute a carrying task
normally performed by two humans. One human was the leader and the
other a follower. The robot replaced the follower leaving the human in
charge. A simple switch was used to turn down the magnitude of damping
when a certain velocity was exceeded.

For our test, we need to determine what that certain velocity is. Velocity data
is checked from previous tests (the test where mass and the magnitude of
damping were changed) and based on this data, we determine that switching
should take place at 0.02 m/s. The parameters of our velocity switch are set
out in figure 19.
This simple switch will be called an on/off switch, but we designed a more sophisticated design. Instead of a simple on/off switch, the magnitude of damping is turned down gradually in a linear manner. During the performance phase, the magnitude of damping is kept constant, but when a certain speed is exceeded the level of damping decreases until it reaches zero at a certain speed. This type of switch will be called the linear switch. The underlying idea is that linear switching will lead to more stable switching behaviour. Tests are run to examine which switch is the most stable.

In figure 20, the parameters of the linear switch is shown. As can be seen, the magnitude of damping reaches zero at the speed of 0.1 m/s. This speed was determined by trial and error.

![Graph showing damping with respect to velocity.](image)
5.3. Results
The on/off switch, that is pictured in figure 21, has an average transitional power (the power used by the operator during the transfer state) that is lower than the average transitional power of the linear switch, shown in figure 22. The reason for this difference is that the magnitude of damping (red dashed line) of an on/off switch changes instantly, while the magnitude of damping of the linear switch changes gradually. Therefore, the magnitude of damping in the former case remains longer at a zero value, which requires less power. The velocity line (blue line) of an on/off switch shows an oscillation near the destination point, while the linear switch does not have such oscillation. When comparing the on/off switch with the linear switch, it is clear that the linear switch is more stable near the vicinity of the destination point and the on/off switch requires less power. The test subject experiences a gradual increase of the magnitude of damping when he slows down near the destination point with a linear switch. This will help him transition easily back to the performance phase. For this reason the linear switch is chosen. See the Appendix for all the corresponding Matlab and Simulink files used for building both switches.

![Fig. 21. Switching behaviour of a simple on/off switch. Please note the overshoot when velocity decreases to normal levels](image-url)
Fig. 22. Switching behaviour of a linear switch. Please note the lack of overshoot when velocity decreases to normal levels.
6. Actual Welding
In the previous tests welding was emulated with an airbrush. However for this new test a real welding torch - a TIG (Tungsten Inert Gas) torch - will be connected to the HapticMaster. TIG welding requires a high level of skill. Therefore, it is the prime candidate for robot assistance. Further there occurs no splatter of metal particles, little amount of gas and smoke and it can be used without an external filling material, these characteristics make TIG welding advantageous in a testing environment with unskilled welders.

Fig. 23. A TIG torch connected to the HapticMaster

Fig. 24. A TIG torch with the cable connected to the HapticMaster
6.1. Experiments with actual welding

Number of unskilled welders is asked by us to weld a single straight line with and without robot assistance. After finishing with welding, the results of both tests will be compared visually. It is expected is that the difference between welding with and without robot assistance will be comparable to the difference between a skilled and unskilled welder. In other words, we expect a straighter more uniform weld with robot assistance.

The test subjects are given the opportunity to practise beforehand to familiarise themselves with welding. Hereafter, they will first weld with robot assistance before welding manually. As a result, any possible learning effect will be in favour of manual welding because it takes place at the end.

The following test parameters are chosen:

- Robot assistance will be generated with the HapticMaster’s variable impedance control, which is exactly the same as the one used in previous tests with the airbrush (100 N•s/m and linear switching behaviour);
- The materials used are S235 blank steel of dimension 300x50x4;
- The materials are welded together with no gap, no groove and no filling material; and
- The TIG torch current will be set at 80 ampere for all cases.

*Fig. 25. Subject welding manually. The picture clearly shows that the operator carries the weight of the torch and the cable.*
6.2. Results
The difference between welding with and without robot assistance could be clearly seen during welding. The vibrations of the welder during manual welding were clearly higher than the vibrations while welding with robot assistance. The test subjects also noticed these increased vibrations during manual welding. The test subjects subjective feelings found welding with robot assistance more comfortable, because of the decrease of vibrations and the weight compensation. The fact that the HapticMaster carried the cable felt liberating for them, literally lifting a weight from their shoulders. Visual inspections of the welds show that there is less undesired movement with robot assistance. Figure 26 and 27 show that the welds are straighter and more uniform in width when the test subjects weld with robot assistance. They are better able to track the seam with robot assistance than without. Figure 28 shows a manual weld has lots of “bumps” and “valleys”, while the weld executed with robot assistance is a lot flatter. All figures show an improvement when welding is done with robot assistance.

**Fig. 26.** Results of manual welding (below) and welding with robot assistance (above). The one with robot assistance is straighter.
Fig. 27. Results of manual welding (below) and welding with robot assistance (above). The one with robot assistance is straighter.
An expert welder was requested to look at the welds and to give his opinion concerning the difference between welds done with and without robot assistance. He agreed with our assessments of figure 26 and 27. He said that with robot assistance the test subject was better able to track the welding seam, there was less variance in width and the velocity was more constant. He also noticed the “bumps” and “valleys” in figure 28. The reason for this was that the angle of the torch changed. With robot assistance the angle is set and cannot be changed, because the HapticMaster has only 3 DoF. By taking away a degree of freedom, the welding task becomes easier.
7. Conclusion and future work

The goal of this paper is to use a robot to assist with manual welding. This robot assistance comes in the form of the HapticMaster. The end effector of this HapticMaster will have impedance characteristics with damping and mass being the most important parameters. Both the effect of mass and damping are analyzed. Damping reduces the variance of undesired movements with an optimum that is found at a magnitude of 100 N•s/m, while mass does nothing useful and is disregarded. Because high magnitude of damping means that moving a torch requires too much energy and time, a velocity switch is built. Two alternatives for the switch are compared. Firstly, a simple velocity switch that switched damping off when a certain velocity is exceeded. Secondly, a switch that has a linear decline when a certain velocity is exceeded. The first one is called an on/off switch, while the other is a linear switch. It is found that the linear switch has a much more stable switching response compared to the on/off switch. At the end, we did tests with respect to actual welding. Here the difference between manual welding and welding with robot assistance are examined. It is found that welding with robot assistance is more stable and the welds are straighter and have a more uniform width.

By doing all these tests we found there was room for improvement. With regard to the linear switch, figure 29 shows that there are two large force peaks at the beginning and at the end of switching.
Studying the velocity graph, shown in figure 30, it can be clearly seen that there is a sudden change in slope at 0.02 m/s and another one at 0.1 m/s. If we are able to smooth out this sharp transition, it can be possible to avoid sudden increase of force and to minimize jerky movements.

Fig. 29. Switching behaviour of the linear switch. Please note the two large peak forces.

Fig. 30. By smoothing out the transitions, the jerky movements can be minimized. The dashed line shows the improved and smooth velocity switch.
When studying figure 27, the transfer phase can be immediately detected by the increase of force. In the current state, the test subject has to increase force, which in turn increases the velocity. While accelerating the magnitude of damping is still high, until the threshold velocity (0.02 m/s) is reached. The switching will be smoother when the force is used to determine the switching point. The force fluctuates too much to be able to determine the end of the transfer phase, but the velocity can be used for that. A switch can be designed that turns the magnitude of damping down when a certain force is exceeded and that turns it up when a certain velocity is reached. This switch would be more complex to design, but the results could be worth it.
References


Appendix
Simulink Linear Switch
Simulink On/Off Switch
### MATLAB Function

```matlab
function position = change_damping_magnitude(damping_number, Dx, Dy, Dz)

global CFcsHapticMaster CFcsDamper CFcsConstantForce CreateConstantForce
SetBaseParameters SetForceGetPosition GetParameter_3 ScanCurrentForce
SetForceGetPosition

data = [Dx, Dy, Dz];

% Assign the force in Maptic to force_number
[obj_number, getdata] = maptic(CFcsDamper, SetBaseParameters, 2, data);

data = (1:15)*0;
[obj, getdata] = maptic(CFcsHapticMaster, SetForceGetPosition, 0, data);
position = getdata(1:4);
```