Final Report

Shadow robot

Shadow Robot- Bandsaw cutting of Beef Shank- Stage 1

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1.0 Executive Summary

The goal of this Stage 1 project is to provide the industry with working knowledge on state-of-the-art telemanipulation technologies, and their potential applications. The project will gain this working knowledge by control a UR10e Cobot with a telemanipulator and thereby removing human work force from the hazardous meat processing tasks, when cutting beef shanks on a band saw, selected as a use case.

The project started off by taking the two selected technologies: The Virtuose 6D and the VIPER™ System respectively and configuring them with the necessary hard/software so that they could manipulate a Universal Robots UR10e Cobot.

The two manipulators where then tested for the potential capabilities they provide in a lab setting for basic precision and control experience for the operator, in iterative steps, first without product, then using product dummies, and finally using real product beef shanks during MS1[1] to MS4.

Figure 1. Cutting 50mm[1] shank cuts on bandsaw by means of a telemanipulator and a robotic arm

The major difference between the two manipulators chosen and tested was that the Virtuose 6D comes with force feedback in the handle. However, when real product was processed and tested it became clear that it was important for a successful operation to have the force feedback. The force feedback helps the operator to navigate through the bandsaw without causing any load error[2] to the Cobot. Likewise, it was useful to make the correct placement of the meat against the guide land, and it was concluded necessary to have some sort of other feedback, than the just visual view of the operation, either direct or remote by means of monitoring camera set up. Hence the final processing, testing and demonstration activities was focused on Virtuose 6D manipulator.

[1] Milestone, the project has a total of 5 Milestones.
[2] The UR10e has a payload on 12,5 kg.

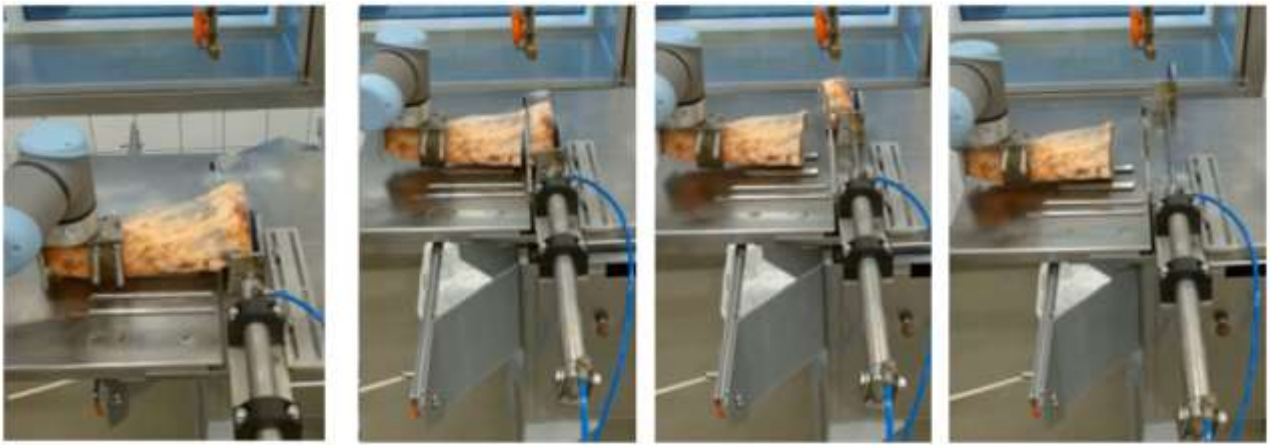

Figure 2. Shows the cutting of slices in steps, with the actuator both serving as land and for pushing out product after cutting

Concluding on the project overall objectives it was demonstrated possible, with some training to use a telemanipulator like the Virtuose 6D controlling a Cobot, to execute a process like cutting shanks on a bandsaw, also with the operator placed at a remote location. The quality of the cut samples was of acceptable thickness variation within the specification of 50 [mm] ±10 [mm].

In this view the project has been successful and met its targets fully.

The concept and value of shadow robotics in the meat industry, may offer advantages in several forms:

- Remote operations (eg taking operators off the factory floor and allowing sourcing at locations where they are
- Reducing WHS issues of dangerous operations
- Introducing and sourcing of remote operator that are normally not interested or resourceful in a meat plant operation
- Splitting tasks between multiple remote operators, rather than using local resources at repetitive task for long hours
- Fast tracking fully automated robotic processes or design of dedicated machines for a process allowing labour reduction

The project recommendation for next stage is based on the experience from the Shadow Robot Stage 1 project and the live demo for AMPC and following discussion and dialogue.

Stage 1 has demonstrated that the entire telemanipulation technology has potential, especially in the field of remote operations and for combining the robot path planning with the skilled movement from an operator into one process. For real industrial applications it will require some of the fundamentals to be better in place:

- Senses (improved visual presentations/environments, sounds, vibrations, eg virtual environment)
- Technology (robots with sufficient payload and versatile cobots (larger payload), more flexible and programmable telemanipulator settings, fully developed tools for the chosen task)

- Operator situation (training time, adaptation, demonstrating usage under production- like condition, either near/at- or in-line

DMRI will in dialogue and consultation with industry end-users and AMPC select relevant use case(s) to be proposed for demonstration in a stage 2, - proposed with establishing: dedicated test scenarios of the control senses needed for optimum telemanipulation executed from remote, an improved feedback environment, a robotic platform without payload limitations causing issues, dedicated tools complete for the process and additional/improved manipulators and dexterous hands if necessary.

2.0 Introduction

Cutting shanks into osso buco pieces on a bandsaw is a risky operation even if the bandsaw has a guide land, where the shank can be placed against to ensure the orientation and the thickness of the slides[3].

The first cut the operator must do is without any guide land because the shank must have an initial cut to establish a flat plane. By having a flat surface to press against the guide land will ensure that the thickness of the following slides will be within the tolerance.

Lately commercial telerobotic solutions that integrate with low cost cobots have become commercially available which together may offer a solution to remove the Operator from the hazardeous process on the slaughter floor.

The goal of this Stage 1 project is to provide the industry with working knowledge on state-of-the-art telemanipulation technologies, and their potential applications. The project will gain this working knowledge by control a UR10e Cobot with a telemanipulator and thereby removing human work force from the hazardous meat processing tasks, when cutting beef shanks on a band saw, selected as a use case.

3.0 Project Objectives

The project objectives are:

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- To investigate the feasibility of at least 2 telemanipulation technologies in removing human work force from the hazardous meat processing tasks, when cutting beef shank on a band saw
- To develop a methodology using telemanipulators for the task meeting capacity and quality requirements
- To provide the industry with working knowledge on state-of-the-art telemanipulation technologies, and their potential applications

[3] 50 [mm] ±10 [mm]

4.0 Methodology

The methods applied in MS1 to MS5 were following:

A. Develop and test pilot plant experience with the 2 technologies (Virtuose 6D telemanipulator and the VIPER™ System tracker) and gain understanding for the potential capabilities they provide. This knowledge was used to plan the later test setup. Software interfaces was built and configured, and integration between tele manipulators and robots was set up.

B. Design and construction of a safe testing site, for beef shank cutting with band saw, executed by a cobot controlled remote by an operator with telemanipulator, ensuring that safety measures are undertaken to protect equipment from damage and personnel from harm. The use of safe zone in the robot software was also useful to this end. A mechanical guide was used to ensure a consistent cut thickness every time.

C. Tests for the necessity of force feedback in the operation loop was made. The capacity and quality of the cutting was tested for Virtuose 6D telemanipulator, as the lack of force feedback, as is, in the VIPER™ System did not permit safe control and cutting, as the operational value of force feedback was high.

D. Develop and demonstrate in iterative steps on real meat product the shadow robot cutting proces

5.0 Project Outcomes

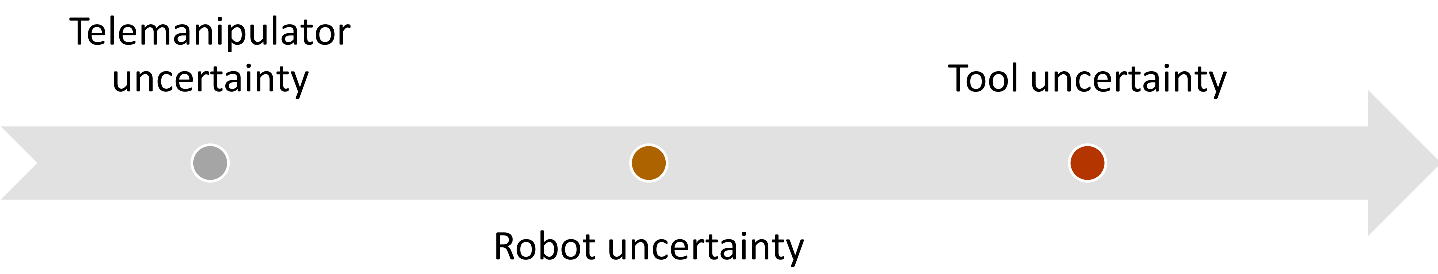
Cutting shanks into osso buco slices on a bandsaw is a risky operation even if the bandsaw has a guide land, where the shank can be placed against to ensure the orientation and the thickness of the slides[4]. The first cut he/she must do is without any guide land because the shank must have an initial cut to establish a flat plane. By having a flat surface to press against, enables the guide land to make sure that the thickness of the following slides will be within the tolerance.

The project has investigated the feasibility of 2 telemanipulation technologies (Viper tracker and Virtuose 6D) to control a Cobot holding a shank while cutting:

The Virtuose 6D	VIPER™ System
	

Figure 3 and 4: Manipulator tools

The Viper tracker is a commercial product, running on DMRI software and the Virtuose 6D is a commercial product both hardware and software wise. The precision for the entire system has been defined into 3 categories of potential uncertainty.



The project scope was not on robot tool design and therefore the uncertainty of the tool was assumed ≈0 [mm] This was carried by making a simple clamping-tool for the shank testing, so that it was fixed in a rigid position.

[4] 50 [mm] ±10 [mm]

Naturally this was an assumption and during the many tests it has been observed that the test-tool needed to be improved. Because the meat was not completely fixed.

The Viper position accuracy is sensitive towards other magnetic fields. Therefore, a minimum distance test was performed[5] to showcase that the Viper sensor should not be placed in a distance less than 25 centimetres from source of a magnetic field.

When the entire Viper system (Viper, robot, and tool) was working at a speed of 5 [cm/s] then the precision was ±3 [mm]. This was determined by the "10 line" test[6].

The project team developed a methodology and safety set up for using and testing telemanipulators for the task. This necessary to research and demonstrate in a hardware and software control design which together with a remote Operator can test and demonstrate how capacity and quality requirements in the use case process can be met.

Figure 5 and 6: Pilz safety system in ceiling(left), an Pilz zone in pointers on floor, traffic light behind, yellow camera above robot provides close up monitoring on a screen for the operator using the Virtuose 6D manipulator

Tests showed that it was easier to carry out the control of the manipulator handle, by **following the action on a screen** projecting the image from a camera placed parallel to the bandsaw blade and the guide land, as compared to follow it from a distance directly while using the manipulator. This gave a closeup and almost natural view of the process and allowed looking close to the manipulation of the shank when cutting, almost like an Operator carrying out the process manipulating product by hand, but without the risks of hands in proximity of the saw blade.

The user experience was also tested by 11 untrained users. They were given a short 3-5 min introduction to the setup actions and boundaries, and the process and a few minutes to accustom themselves to the movements using the manipulator handle before actual cutting. The initial first cut had been done beforehand, to give the user a good reference. Most of the untrained operators were able to carry out cutting one entire shank within the desired tolerance[7]. The experience feedback collected indicated that several operators felt that there was a lack of 3-dimensional feeling. The input from a 2-dimensional screen and the force-feedback might be supplemented to make

[5] Look Section 9.1 Appendix 1
[6] Look Section 9.2 Appendix 2

[7] Look Section 9.3 Appendix 3

the experience more intuitively, to allow for a faster learning, and more comfort in controlling the process enough to operate the setup under full control. This might be supplemented by adding a more 3D or virtual like environment for the operator.

Irrespective it was shown relatively easy to get aquinted with the manipulator handle and carry out a process, it also clear that there is a learning curve to achieve finer precision, and also to process and manipulate product efficiently at high speed. This is in principle not different in the training of human operators in a new hand skilled operation. It is a process and skill learning that will not necessarily be for everybody to master. Similar it is not everybody who will have the prerequisites to use a gaming controller, or learn controlling the joysticks in a modern digger /excavator.

The gripping tool had a big role in terms of performance and uncertainty, (though not a target for this stage). The first tool could not provide sufficient steady grip on all the shanks, mainly because of the relatively big size, weight variation of the shanks but also because of temperature, eg frozen vs chilled shanks. So, it was necessary to introduce some modification and improvements to the tool, to ensure that the meat would not slip under the process.

Capacity of the system was optimized by introducing simple “slice removal”, by an actuator, both serving as land for the aligned cut surface and pushing away the slice after cutting. This was integrated in the manipulator handle, which activated an air cylinder that pushing the sliced meat away. This gave the operator the possibility to complete the full process in one continued operation.

Another capacity optimization was to tweak the control ratio between the manipulator and the robot. From 1:1 to 1: 1.5. This introduces more sensitivity, but also the possibility to move faster with the robot. In consequence this gearing for the operator reduces the length of his arm movements, and in practice it meant that situations were avoided, where at a 1:1 control, the clutch/ realignment sometimes had to be used to reach and complete a process.

The major difference between the two manipulators chosen and tested was that the Virtuose 6D comes with force feedback in the handle. However, where real product was processed and tested it became clear that it was critical for successful operation to have the force feedback, to navigate through the bandsaw without any load error[8] from the Cobot. Likewise, it was useful to make the correct placement of the meat against the guide land, and it was concluded necessary to have some sort of other feedback, than just visual view of the operation, either direct or remote by means of monitoring camera set up. Hence the final processing, testing and demonstration activities was focused on Virtuose 6D manipulator.

Concluding on the project overall objectives it was demonstrated possible, with some training to use a telemanipulator like the Virtuose 6D controlling a Cobot, to execute a process like cutting shanks on a bandsaw, also with the Operator placed at a remote location. The quality of the cut samples was of acceptable thickness variation within the specification of 50 [mm] ±10 [mm].

In this view the project has been successful and met its targets fully.

[8] The UR10e has a payload on 12,5 kg.

6.0 Discussion

During the testing in the pilot plant with meat it became clear that the TRL[9] of the telemanipulator is not yet at a sufficient readiness level where it can be a part of everyday equipment. The conclusion comes from seeing open-loop regulation issues between the Cobot and the telemanipulator, this introduced an unwanted oscillation in the robot arm.

The entire setup/time with the wiring and control reset between the safety system of the robot towards the resetting of the telemanipulator, when a collision-error[10] occurs was significant. The level of needed handling and knowledge falls under the categories of development, however not difficult to overcome.

One possibility will be to get extension software for the Virtuous, so that it could manipulate an industrial robot or upgrade the payload on the Cobot, simply by choosing a bigger Cobot. To go over to an industrial robot will be preferred in terms of removing the complexity of the entire system.

It would also be possible to add some modification wiring to the system. This could improve the user friendliness of the entire setup and there by remove many of the obstacles for having a continuous working pace. Given the scope of this project stage it is not possible to conclude how long time an operator would be able to keep up processing at desired quality and capacity. As is, in the present system full control of any movement is now necessary, however many of the actual moves seems within reach of a fully automatic control in the system, and thus only requiring shorter Operator validation or more delicate manipulation in the critical steps, after which the system can work fully automatic. It is envisaged that such a mix of automatic-manual-automatic-manual- control interchange would allow for both capacity improvement and reduce the control load on the operator. An area that should be researched in following steps.

A larger than expected value was discovered by executing the operation while manipulating the shank trough the bandsaw blade, through the Cobot. By controlling the Cobot through the telemanipulator, another dimension of insight in how many potential obstacles there can be, seen from the controlling/automation perspective. This is a valuable discovery which may be applied in developing other semi- or fully automated processes faster.
Looking from an automation perspective, then the telemanipulation handling have reduced the numbers of unknown factors in terms of automating an operation.

It has also introduced a new insight in the area known as “known unknown automation” – In this area there are usually lots of human senses or many years of practical experience present, making it hard to automate. But by combining the operator with a telemanipulator and a robot/Cobot, then it would be easier to take on an operation like eg: splitting the carcass, quartering the side, or performing a difficult deboning cut, all processes which are hard and requires skilled operations.

This way it is possible to utilize the skills from the operator to determine and guide the robot tool (blade) to the starting position of eg the cut on a carcass or product to be cut. Here the operator can do the difficult part of the operation which is difficult to automate for sensing or mechanical reasons. Then when the difficult part[12] is over and the operator has navigated the robot tool through the bones and joints, then he/she can activate a digital output from the telemanipulator and trigger a fixed robot path. Here the robot is being utilized for precision and speed. By this segmentation of the process, the operator can be used where skilled path planning or location are needed, and the

[9] Technology readiness level
[10] Exceeds payload of robot
[12] This is usually to guide a robot tool through bones or joints. Usually, vision systems can determine the starting point of a robot path, but the system has a hard time navigation through the tissue, because of the complexity.

robot path planner can be used for precise and fast movements when not.
The combination of the two systems should result in better work environment for the operator and increase the quality and capacity.

The concept and value of shadow robotics in the meat industry, may offer advantages in several forms:

- Remote operations (eg taking Operators off the factory floor and allowing sourcing at locations where they are available
- Reducing WHS issues of dangerous operations
- Introducing and sourcing of remote operator that are normally not interested or resourceful in a meat plant operation
- Splitting tasks between multiple remote operators, rather than using local resources at repetitive task for long hours
- Fast tracking fully automated robotic processes or design of dedicated machines for a process allowing labour reduction
- Increase capacity and reduce working environment for complex operations, by joining the robot and the operator movements.

7.0 Conclusions / Recommendations

The project recommendation for next stage is based on the experience from Shadow Robot Stage 1 and the live demo for AMPC and following discussion and dialogue.

In the development process of Shadow Robot Stage 1, it became clear that the entire telemanipulation technology has a great potential, especially in the field of combining the robot path planning with the skilled movement from an operator into one process. By doing this it will require some of the fundamentals to be better in place:

- Senses (visual presentations/environments, sounds, vibrations, environment)
- Technology (robots with sufficient payload and versatile cobots (larger payload), more flexible and programmable telemanipulator settings, fully reliable tools, additional shadow tools/manipulators)
- Operator (training time, adaptation, level of technology understanding)

DMRI suggest that a next stage should undertake one or two new processes, to be defined in close dialogue with the AU industry.

This could be selected in consultation with AU processors and AMCP and inspiration from on-site visits at processors in AU/ or EU operations, where the case selection should be based on a process that consists of eg: a complex starting point or skilled movement and a fixed simple path, or a hazardous operation and area of WHS issues or combinations of above .

It is envisaged necessary to upgrade the testing environment to overcome several identified challenges in stage 1.

- The manipulation should rather be an industrial robot or a higher payload Cobot. This is to overcome the observed communication errors causing risk of unwanted collision error.
  It would also be a target to set up an improved remote-control room for the operator providing for longer term working periods this will build on the experience gained in Stage 1.

In a following project Stage is suggested to have several milestones:

MS 1: Initial improved control room layout for handling remote operation cases.

- **Technology toolbox** (introduction of improved or additional shadow robotic tools eg.: Alternative controller solutions similar Gaming controllers, more gearing options or stepwise gearing, split control processing mixing remote control with partial steps being fully robot controlled, Dexterious robotic hands (www.shadowrobot.com), tracing suits that would allow understanding and improving manual operations and faster identification and implementation of processing steps that can be fully automated by dedicated tools, machines or industrial robots

- **Feedback** selection of enhanced sensor and feedback technologies that can give the remote operator the necessary detailed feedback to execute the operation at high speed and sufficient quality. Additional 2D and 3D images. Full 3D Virtual environments imaging the real processing environment. Enhance Sound feedback from the environment/proces to the operator.

The Initial test room layout will be based on user experience and learnings from Stage 1.

MS 2: Control room setup, case-, robot- and tool selection.

Process identification: identifying-and matching industrial processes that has a potential for ultimate use in industry as a commercial viable way of processing, by means of remote labour and/or reduced labour on the processing floor

The **robot selection** will be based on the chosen case actual needs respective payload criteria and the control access towards telemanipulator.
The control room layout chosen will be validated by having a user test of serval instructed people and finished with a live demo between DMRI and AMPC.

MS 3: Setup test facility with robot and begin initial test.

DMRI will establish a working set up/robot cell if necessary, which can be manipulated remotely. The cell will be in a slaughterhouse environment as feasible, relevant for the selected operation and with respect to the robot size.
If it's not possible to establish a robot cell in a slaughterhouse – then a test cell will be placed in the DMRI Pilot plant. The Initial testing will be done in steps to ultimately be performed remotely. The testing should focus on the accessibility with the system and the quality of the performance with respect for a realistic Operator working scenario.

8.0 Bibliography

Milestone report 1 – submitted 19/08/2021 to AMPC

Milestone report 2 – submitted 17/09/2021 to AMPC

Milestone report 3 – submitted 13/11/2021 to AMPC

Milestone report 4 – submitted 14/01/2022 to AMPC

9.0 Appendices

9.1 Appendix. Viper precicison as affected by metal/magnetic field

The precision at 25 cm distance towards another magnetic field also shows the precision of the manipulator with the optimal conditions. So, the uncertainty is ≈0.5 [mm] for any displacement of the sensor in the working arear of the tracking sensor.

The effect on the Viper accuracy from metal at different distances

Distance from sensor Position	Position accuracy [cm]	Orientation accuracy [°]
5 cm	1 cm	1°
10 cm	1 cm	1°
15 cm	0.3 cm	0.3°
20 cm	0.5 cm	0.5°
25 cm	0.05 cm	0.05

9.2 Appendix. Precision testing of the Virtuose 6D set up

Both the UR-robot and tele-manipulator had a pen attached at the flange and end of the handle(respectively) to draw lines on paper.
The setup consisted of 2 coordinate systems to be drawn upon. One for the tele-manipulator and one for the UR-robot. These 2 coordinate systems were used to compare the result of the UR-robot to the input from the tele-manipulator.

When the two coordinate systems is lined op respectively, the operator manipulates the UR-robot in position to draw a line. This is done by using the clutch. When the robot is in position, the operator places the tele-manipulator on the same line (in its own reference coordinate system) as the UR-robot. Now are the tele-manipulator and the UR-robot aligned and the operator can begin the line test.

The test were done by doing 5 lines, then recalibrate (same procedure as above). After recalibration 5 lines are done again. The accuracy of the test is determined by the listed factors above. These alignments are measured by a ruler, this gives a precision of 1mm pr. parameter.

The result of the test showed that the lines are not as even than those drawn by the operator. This could be caused by the friction between the plastic and paper or if the calibration is not 100% correct or slightly angled when placed on the paper again. However, the deviation from the first stroke to the last stroke is within 3 millimeters, compared to a straight line.

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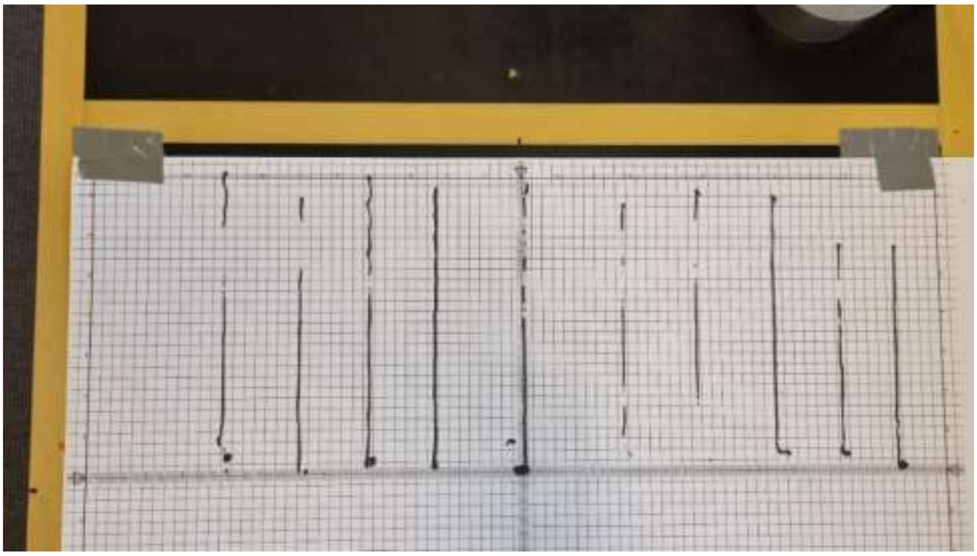
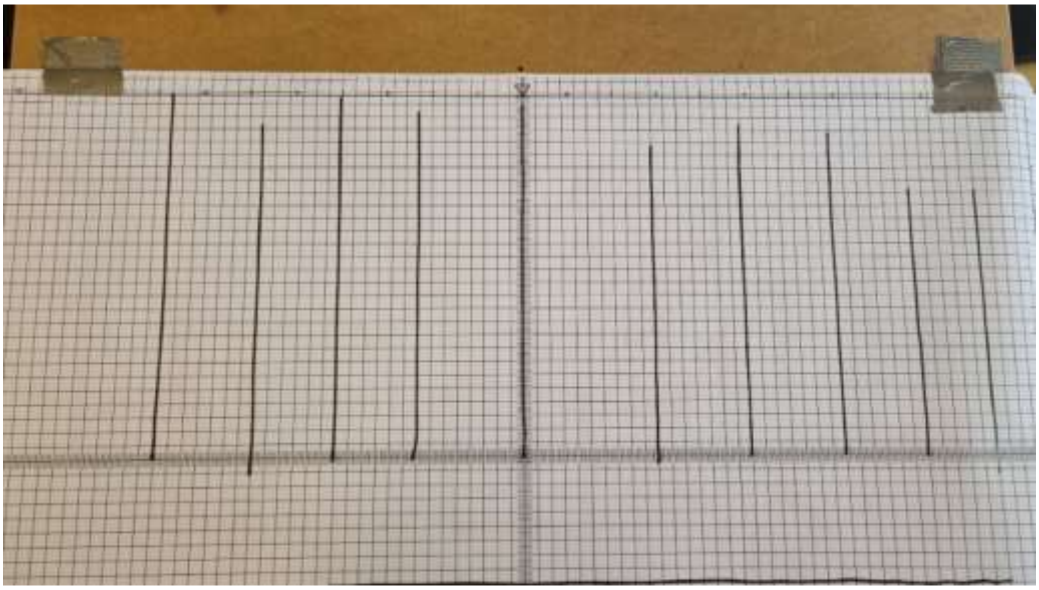


Figure 1.UR lines – result – shadow controlled

11 

12 *Figure 2.Operator lines by moving the Virtuose 6D manipulator*

9.3 Appendix. Beef shank thickness of slices as achieved by newly introduced operators

	Cut number 1 [cm]	Cut number 2 [cm]	Cut number 3 [cm]	Cut number 4 [cm]
Test person 1	4,8	4,5	5	4,4
Test person 2	4,4	4,6	4,8	
Test person 3	4,5	4,8	4,8	
Test person 4	4,7	4,6	4,7	4,7
Test person 5	4,4	4,8	4,9	4,7
Test person 6	4,5	4,8	4,8	
Test person 7	4,8	5,4	4,4	
Test person 8	5,2	5,1	4,9	4,7
Test person 9	4,7	4,8	4,5	
Test person 10	4,2	3,6	4,5	3,5
Test person 11	4	4,9	5	