3D Smart Sensing and Flexible Task Programming for On-Line Trajectory Adaptation in Fast Surface Treatment (3DSSC)

Flexible Robotic Solutions, Belgium (coordinating partner)

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Section 1: Executive summary

This experiment was related to the scenario where a commercial industrial robot with a real-time PC interface is equipped with smart 3D sensing to perform a new task: removing the thin coating of a block of cheese using a planing tool. The sensors are mounted on the robot end effector and hence sensing the surface of the block and removing the coating are performed in a single robot motion ('on-the-fly' sensing).

A first objective was related to the execution speed of the de-coating process. The developed prototype was expected to perform not more than 30% slower than a skilled worker. A human operator using a planing tool can remove the coating of a block of cheese in around 90[sec]. The presented results of the developed test setup suggest an execution time of around 120[sec] for the robot, which is around 30% slower than an operator. However, we would like to emphasize that, after this experiment, there is still room for improving the planing speed.

Another important objective is to obtain a higher accuracy of the de-coating process. When an operator uses a planing tool to de-coat the block, the amount of cheese loss is around 5-6% of the total weight of the block. Using the technology developed in the 3DSSC experiment, the robot can be controlled with a dynamic accuracy of a few tenths of a millimeter, resulting in a cheese loss around 4.5-5%.

Another objective of this project, with focus on research, is to show the benefits of a system architecture, control software and the Orocos RTT real-time software. KU Leuven's *eTaSL* software is used to convert the task specification and control strategy into constraints for an optimization problem that is solved in real-time. *eTaSL* provides a rather simple syntax to define constraints with different priorities, weights and control gains. As shown by this experiment, this results in a flexible software environment where it is easy to change and tune the task specification and control strategy.

Even though this first prototype is not up to an industrial standard yet, the methodology is reliable enough to be extended to a fully automatic system meeting the requirements of the food industry.

A patent application "Method and apparatus for robotic surface following and treatment" was filed. A journal publication co-authored by the academic and industrial partners is planned on *eTaSL* applied to coating removal as a use case to demonstrate *eTaSL's* capabilities.

At the end of the project there is very strong commercial interest from two big companies to further develop this demonstrator into real industrial implementations, which shows the industrial relevance and potential impact.

Section 1.1: Milestone overview

#	Description	status
M1	Early System Integration	Timely achieved
M2	System Operational	Timely achieved
M3	Experiment Show-Case	Timely achieved

Section 1.2: Deliverable overview

#	Description	status
D1.1	Revised experiment specification and planning	submitted
D1.2	Early integration (demonstration of laser sensing and force control implementations)	submitted
D1.3	Experimental system & algorithm description	submitted
D2.1	Software architecture	submitted
D3.1	Final demonstration	submitted
MMR	Multi-Media Report	submitted
SB	Story Board	submitted
RIF	Report on RIF visit outcome	deviated

- RIF: There was no appropriate robot for our application (payload, working range, fast interface) at any of the RIFs, whereas we had access to such robot + an advanced software environment, first at KU Leuven with the KUKA LWR robot, and later at the FRS premises with an industrial KUKA KR16 robot.

Section 1.3: Technical KPIs

#	Description	status
1	Cycle Time - not more than 30% slower than manual work	Achieved
2	Minimize the material losses - 0.5-1% lower than total weight with manual work	Achieved
3	Development of a 3D sensor set-up with 1D laser - Accuracy : +/- 1 mm - Width of the line covered by the laser sensors up to 30-40 mm - Distance of laser sensors to surface: ~ 100 mm - Curvature, i.e. variation of depth over the scan line: +/- 20 mm	Achieved
4	Force control - prototype of 1 DOF passive force control system with adjustable force setpoint	Not achieved

5	Integration of 3D sensing and force control - Integrated system , but still w/o the advanced constraintbased SW architecture	Not achieved
6	Implementation of software architecture for constraint-based trajectory generation and motion control - Real-time trajectory adaptation and motion control - Accuracy of generated motion: +/- 1mm; verified by measuring the excursions executed by the passive force control system	Deviated
7	Experiment showcase - Automated system with on-the-fly 3D surface measurement and trajectory Adaptation	Achieved

- KPI4, KPI5, KPI6: It turned out that force control was not necessary, i.e. all major objectives could be achieved based on purely geometric control, and force control was even not desirable. Therefore, the force control option was not pursued, making KPI4 and KPI5 irrelevant. KPI6 only deviates in that force control was not implemented. In fact, a much higher accuracy was obtained than planned, around +/- 0.2 mm.

Section 1.4: Impact KPIs

#	Description	status
1	Direct labour cost saving in comparison to manual work	Achieved
2	Cheese loss reduction	Achieved
3	Selling Price	Achieved
4	Scalability to other manufacturing operations (deburring, grinding, polishing) and transfer to other industrial branches outside food industry.	Not Achieved

- KPI4: Possible, but not within the scope of this experiment.

Section 1.5: Dissemination KPIs

#	Description	status
1	Fairs	Achieved
2	Experiment Website	Not Achieved
3	Journal publication	Not Achieved
4	Conference	Not Achieved
5	Media Coverage	Not Achieved

- KPI1: participation in Echord++-booth at Hannover fair, April 2016.
- KPI2: we plan to add a video of the experiment to the FRS website.

- KPI 3 & KPI 4: Planned submission in 1st quarter 2017 on *eTaSL*, with application to coating removal as a use case to demonstrate *eTaSL*'s capabilities.
- We do not consider or plan dissemination on the automation of the process as FRS is working under NDA with two companies towards commercialisation.

Section 1.6: Additional (unplanned) achievements

- A Belgian patent application "Method and apparatus for robotic surface following and treatment" was filed in April 2016 (authors: J. De Schutter, E. Aertbeliën). We are considering extension of the protection to Europe before the end of the priority date.
- Several improvements to *eTaSL* were triggered by this experiment, and KU Leuven made several upgrades of the *eTaSL* software during the project to accommodate the needs of the experiment.

Section 2: Detailed description

Section 2.1: Scientific and technological progress

<u>T1: Development of experimental set-up</u>

- **Revised experiment specification and planning (see also D1.1):** Interviews with potential customers revealed their preference for very fast and very accurate control in view of removing a thin layer of coating at very high speed, with an accurate cutting depth, and with minimal contact between cheese and tool. We therefore opted to concentrate on developing a purely geometrically controlled robot without incorporation of force control. Instead of integrating force control it was much more useful to devote more efforts in accurate surface modelling and control.
- **Early integration (see also D1.2):** This work consisted of hardware integration and software integration.
    - *hardware integration*: we built a tool consisting of a rotating cutting tool with two knives, three laser sensors mounted ahead of the cutting tool, and an outlet port connected to a vacuum cleaner. The tool was mounted on a KUKA LWR-robot at KU Leuven's premises. A calibration routine was designed and tested to obtain the pose of the laser sensors with respect to the robot end effector (accuracy of 0.1 mm). The laser measurement was combined with the robot position measurements, while the relative delays between both measurements were corrected, to obtain very accurate 3D surface points even when moving the robot at high velocity. The measured surface points were shown, together with the robot set-up, in a simulated environment implemented in *rviz.* The robot was interfaced to the software using the FRI interface.
    - *software integration*: a first design of the software architecture was made , linking to KU Leuven's Domain Specific Language, *eTaSL*, which allowed a high-level specification of the robot task using constraints formulated in terms of expressions.
      The biggest advantages are that 1) the task programmer is less burdened with calculating the mathematical derivations involved in the specification of the constraints, and 2) the

task programmer is less burdened with the programming language details, since the underlying framework instantiates the required software components and algorithms from the task description.

- **Experimental system and algorithm description (see also D1.3):**
  - *surface modelling:* A patch of measured 3D points moves together with the measured position of the knife. The width of the patch corresponds to the width of the knife. A local model of the surface is fitted through these points. The local model consists of a doubly curved quadratic surface. The surface estimator uses a fully probabilistic approach, such that a prior estimate of the surface can be incorporated. This allows us to deal with incomplete laser measurement data (e.g. at the edge of the surface, or during the approach phase).
  - *control:* The knife is constrained to follow the surface model in height and in roll. Since *eTaSL* knows the expression of the local surface model, the correct feedforward velocity is automatically generated. Due to the rotational symmetry of the cutting tool, the pitch orientation can be chosen freely. This degree of freedom is used to constrain the laser distance to the laser's measurement range. *eTaSL* automatically calculates the required pitch angle. To achieve accurate control at very high robot velocities, the robot control delay was identified and compensated.
  - *tests* on *wooden block mock-ups:* the surface modelling and control was tested by tracking the surface of wooden blocks (just above the surface). This test was shown at the Hannover Messe (April 2016).

<u>T2: System architecture and software</u> (see also D2.1)

The software architecture proposed in D1.2 was further iterated and refined and resulted in the figure below (Figure 1). Compensation of measurement and control delays, surface modelling and control were all implemented. Modifications to *eTaSL* were specified and implemented to deal with all aspects of this demanding robot task. The results of T2 were used as input for the experimental system in T1 and for the validation experiments in T3.

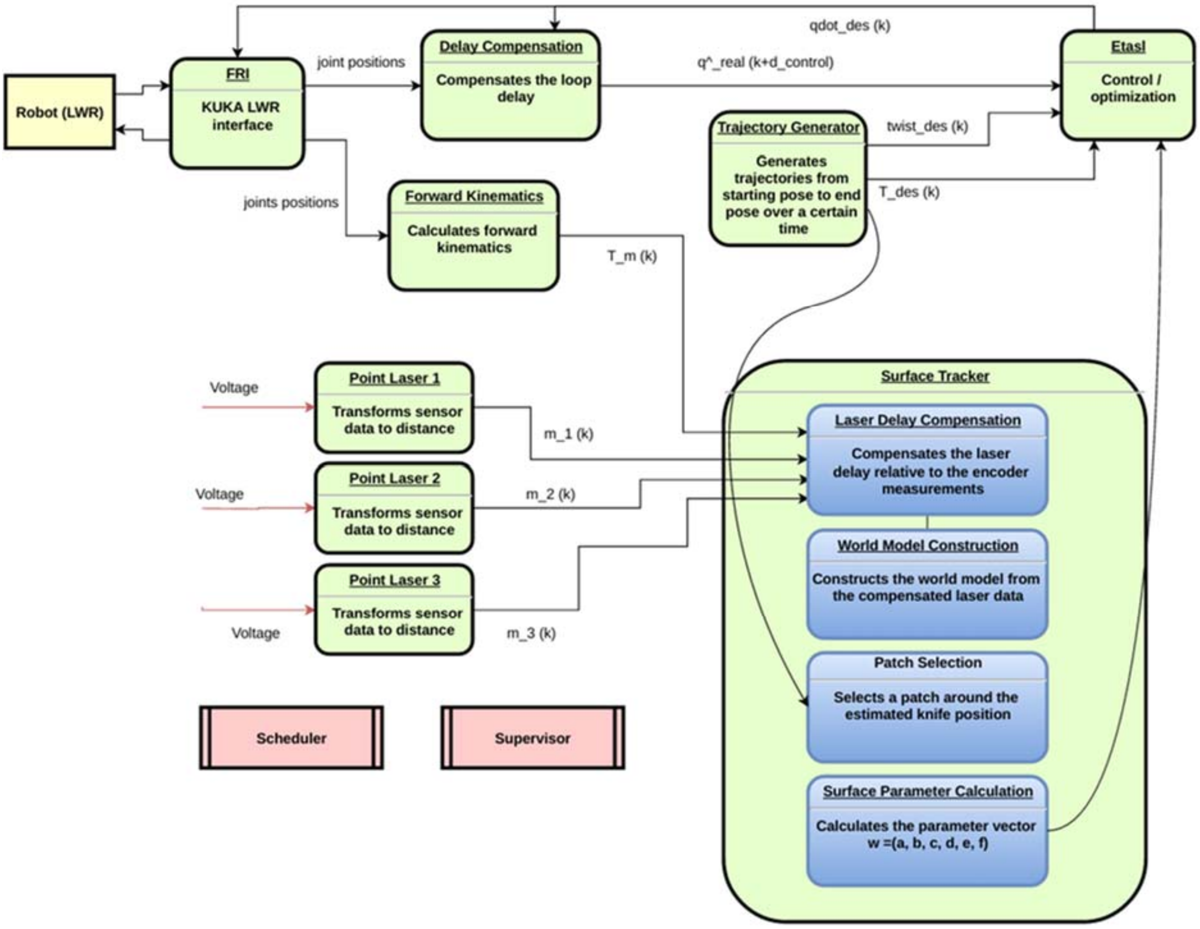

Figure 1: System architecture and software

T3: Validation experiments (final demonstration, see also D3.1)

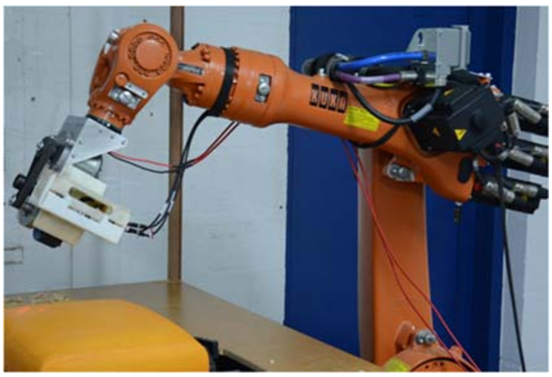

Figure 2a: Proof-of-concept set-up at FRS

Figure 2b: Removed Strips (results at FRS)

The final demonstration was carried out on an industrial robot (KUKA KR16) at the FRS premises and not at a RIF, because: 1) we were able to select the robot with the appropriate specifications (payload and reach), 2) we were able to select the robot with a fast and high quality interface with our control computer, 3) we had good connections with the robot manufacturer to assist us with the interfacing, and 4) the developer of the task specification environment, *eTaSL*, was a member of our team. Therefore, there was no benefit in developing the experimental results in a robotics innovation facility (RIF).

The effort went into: 1) developing the connection between robot and control computer using the RSI interface (instead of the FRI interface); 2) further adding functionality to *eTaSL*; 3) building a higher level program to process consecutive strips; 4) including a variety of safety features to allow autonomous and robust task execution at high speeds; 5) tuning of the task (speed, cutting depth) and control parameters (priorities and weights of the task constraints as well as the corresponding control gains).

Section 2.2: Scientific and technological achievements

A first objective was related to the execution speed of the de-coating process. The developed prototype was expected to perform not more than 30% slower than a skilled worker. A human operator using a planing tool can remove the coating of a block of cheese in around 90[sec]. The presented results of the developed test setup- with an average velocity of 200 mm/s, with peak velocities up to 250-300 mm/s - suggest an execution time of around 120[sec] for the robot, which is around 30% slower than an operator. However, we would like to emphasize that, after this experiment, there is still room for improving the planing speed.

Another important objective was to obtain a higher accuracy of the de-coating process. When an operator uses a planing tool to de-coat the block, the amount of cheese loss is around 5-6% of the total weight of the block. Using the technology developed in the 3DSSC experiment, the robot can be controlled with a dynamic accuracy of a few tenths of a millimeter, resulting in a cheese loss around 4.5-5%.

Another objective of this project, with focus on research, was to show the benefits of a system architecture, control software and the Orocos RTT real-time software. KU Leuven's *eTaSL* software is used to convert the task specification and control strategy into constraints for an optimization problem that is solved in real-time. *eTaSL* provides a rather simple syntax to define constraints with different priorities, weights and control gains. As shown by this experiment, this results in a flexible software environment where it is easy to change and tune the task specification and control strategy.

In addition, several improvements of *eTaSL* were triggered by this experiment, and KU Leuven made several upgrades of the *eTaSL* software during the project to accommodate the needs of the experiment. One important upgrade takes into account the time derivative of an on-line change in constraint weighting when generating *eTaSL*'s feedforward signal. This is very important for highly dynamic tasks, such as in this experiment, in which the weight of the different constraints is changed at run time to make smooth (but fast) transitions between control modes, for example during approach of the cheese block.

The experience with *eTaSL* and its upgrades will be disseminated in a journal paper, to be submitted in the first quarter of 2017. In this paper, application to coating removal will be the use case to demonstrate *eTaSL*'s capabilities.

A Belgian patent application "Method and apparatus for robotic surface following and treatment" was filed in April 2016 (application number: 100014092; authors: J. De Schutter, E. Aertbeliën). We are considering extension of the protection to Europe before the end of the priority date.

The demonstration focused on the low and intermediate control levels to perform fast and accurate coating removal on a single surface strip of a cheese block. At the higher level a small extension was made to demonstrate the processing of several neighboring strips. To de-coat a complete cheese block, the different sides of a cheese block have to be processed, which necessitates turning of the block. This was considered out of scope of the project.

Even though this first prototype is not up to an industrial standard yet, the methodology is reliable enough to be extended to a fully automatic system meeting the requirements of the food industry.

Section 2.3: Socio-economic achievements

Impacy KPI's related to i) direct labour cost saving in comparison to manual work, ii) cheese loss reduction and iii) selling price:

i) If we are able to implement the technology developed in this experiment, it will be possible to uncoat max. 40 blocks in 1 hour (assuming a min. time per block of 90 seconds) by 1 robot (+1 robot to assist in loading/unloading from the conveyor belt and to turn the cheese). If these 2 robots are operational during min. 85% of the year (remaining max. 15% is reserved for tool change and maintenance), then the min. uncoating capacity of a cell equiped with these 2 robots is +/- 300K blocks/year. For a factory which produces 600 Kblocks/year (figure received from industry), max. 4 robots are required. These 4 robots replace the work of 3 teams of 2FTE each (8 hours/day/team, 240 working days, 52 blocks/hour/ operator or 30% faster than the 2 robots, 25,-€ all-in/hour/FTE or 48K €,-/year, excluding cost of the supervisor in charge for supervision and logistics to load and unload the cell). The direct labor cost saving is +/- 300 K€uro/ year.

ii) If the average loss of manual planing of 1 Euroblok (14kg) is 5.5% (0,770kg) and if the industrial target for removing coating with robots is 5.0% (0.700kg) and if the price difference between cheese without coating (4,5€/kg, internal factory price) and cheese with coating (0,5€/kg, external price) is 4,0€/kg and if the factory handles 600 Kblocks/year (figure received from industry) then the total yearly savings are: +/- 170K€uro/year.

iii) Selling price: For a factory which produces 600 Kblocks/year, there are 2 cells with 2 robots required. If the cost of 1 cell (which uncoats 40 blocks in 1 hour with an average loss of 5%) is +/- 500k€, then the expected ROI (return on investment) will be +/- 1 year which is a competitive figure in foodindustry (higher ROI than in manufacturing) .

Figures above are from industrial companies interested in the technology developed in this experiment.

Section 2.4: Dissemination activities

Flexible Robotic Solutions (FRS) participated in the Echord++ booth at the Hannover Messe, Hannover, April 2016.

The experience with *eTaSL* and its upgrades will be disseminated in a journal paper, to be submitted in the first quarter of 2017. In this paper, application to coating removal will be the use case to demonstrate *eTaSL*'s capabilities.

FRS has promising business outlook with 2 multinational companies and is working with them under NDA to prepare commercialisation. Therefore FRS cannot disclose information in the media.

Figure 3: Experimental setup using KUKA KR16

The multimedia report is available at the following location: https://sway.com/qlE13OUl5YaVpc3v , where the robot removes three strips of the top surface of a cheese block.

Figure 4: The robot motion on the cheese block while removing the coating.

Section 3: Resource usage summary

FRS			
	WP8	Salaries of 3 researchers: Dominick Vanthienen (6,5 PM), Keivan Zavari (10,5 PM) and Karel Vander Elst (14 PM) = 31PM on experiment 3DSSC.	162 294,80 €
	WP8	Protection Intellectual Property	5 810,00 €
	WP8	Rental Robot KR16	3 000,00 €
	WP8	Hannover Messe 2016 (Hannover), 25-29/04/2016, Philippe Delforge, Hans Wambacq, Karel Vander Elst, Keivan Zavari	1 634,50 €
	WP8	Custom made tools for proof-of-concept tests	4 919,20 €
	WP8	Custom made interfaces for proof-of-concept tests	3 584,16 €
	WP8	Travel Expenses	1 746,34 €
	WP8	Other Direct Costs as specified in Claim 1	16 870,00 €
			199 859,00 €
KU Leuven			
	WP8	SDD hard drive for the controller PC in the robot-setup	265,00 €
	WP8	Item profiles and connection pieces to build experimental test set-up	9,00 €
	WP8	Item profiles and connection pieces to build experimental test set-up	255,75 €
	WP8	Salaries of 3 researchers: Gianni Borghesan (4,3 PM), Erwin Aertbeliën (1,5 PM) and Bart Theys (0,5 PM) = 6.3PM on 3DSSC	47 095,71 €
	WP8	Hannover Messe 2016 (Hannover), 25-29/04/2016, Maxim Vochten, Enea Scioni, Wim Decré, Yudha Pane	1 375,55 €
			49 001,01 €

Figure 5: Resource Usage Summary

Section 4: Deviations and mitigation

- **Force control:** Interviews with potential customers revealed their preference for very fast and very accurate control in view of removing a thin layer of coating at very high speed, with an accurate cutting depth, and with minimal contact between cheese and tool. We therefore opted to concentrate on developing a purely geometrically controlled robot without incorporation of force control. Indeed, when applying a controlled force to the surface, the amount of material removed depends on 1) the magnitude of the force, 2) the feed rate (tangential velocity), and 3) the material properties. Hence, a detailed and complicated model for the material removal rate is required, with the material properties as uncertain parameters. This also requires additional extensive testing of the material removal model. Instead of integrating force control it was much more useful to devote more efforts in accurate surface modelling and control. With this purely geometric approach we achieved an accuracy that was better than anticipated, which justified our approach.

- **RIF:** The final demonstration was carried out on an industrial robot (KUKA KR16) at the FRS premises and not at a RIF, because: 1) we were able to select the industrial robot with the appropriate specifications (payload and reach), while none was available at any of the RIFs; 2) we were able to select the robot with a fast and high quality interface with our control computer, 3) we had good connections with the robot manufacturer to assist us with the interfacing, and 4) the developer of the task specification environment, *eTaSL*, was a member of our team. In short, all required equipment, software and expertise was available in our team. Therefore, there was no benefit in developing the experimental results in a robotics innovation facility (RIF). It was also more efficient in terms of resources (time spent, travel and accommodation expenses).

Section 5: Future work

While the project focused on the low and intermediate control levels, future work will concentrate on the high level, i.e. task programming. For every type of cheese the following has to be decided:

- optimal width of the cutting knives;
- cutting direction (strips are defined in longitudinal or lateral direction depending on the direction of strongest curvature of the surface);
- programming of consecutive strips, with special attention to the borders of the surface;
- setting and optimization of the parameters (cutting speed, cutting depth).

Following additional features should be developed to extend this experiment to a fully automatic system meeting the requirements of the food industry.

- use laser scanner instead of laser point sensors for higher accuracy.
- determine/verify the position of the block of cheese using a cheap 2D vision camera;
- use only part of the knife’s width to deal with highly curved surfaces; here a trade-off has to be made between reduced material loss and additional cycle time (additional strips);
- perform durability tests.
- include a quality control sensor to check if all coating has been removed and subsequently: 1) repass to remove the remaining coating; 2) adapt the cutting depth for subsequent strips;
- apply adaptive learning: memorize the locally optimal cutting depth as a function of the surface coordinates and use these values as settings for future cheese blocks.

Once this future work is done, it is expected that all goals (see technical and impact KPI’s both 1 to 3, will be fully achieved.

Section 6: Lessons learned

1. While our participation to the Hannover Messe 2016 set a deadline which forced us to reach a sufficient level of early integration, it came too early in the project. As our demo at Hannover 2016 did not show real material removal, it was immature, did not attract the expected attention and did not result in any useful commercial contacts. On the other hand it required a lot of resources to prepare, travel and be present at the booth for the whole period. For this reason we withdrew early May from participating in the Automatica Fair, which was unfortunately not well preceived by the E++ Organising Committee because our we committed

end 2015 for the Automatica Fair. Participation to a Fair at the end of the project would have been much more efficient and impactful.

2. It does not make sense to force a project to go to a RIF if a company has all the necessary (industrial) infrastructure and (application-oriented) expertise in-house. It is better to offer this as an opportunity for projects that lack such opportunities.