Project acronym **pickit**

Project full title **Multi-modal bin-picking for new industrial tasks**

TRL Questionnaire

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# Executive Summary

## Main objectives

In the pickit proposal we said to aim for a higher TRL of the tactile sensor of the grippers, starting at TRL 6. The tactile sensor has been utilized in different bin-picking applications by means picking different parts and so bringing the sensor into real use. We’d like to increase the TRL of the tactile sensor to level 7. The sensor is specialized in detection of the part pose, part loss and the state of a successful grip.

Before the start of the pickit experiment the gripper of a UR 5 was equipped with a tactile sensor and used to carry parts from a predefined position to a deposit station. Furthermore, we have a mobile robot unit, which is equipped with a tactile finger element, using the tactile sensor on a 3-finger kinematical gripper in order to realize different manipulation tasks like the verification of a successful grasp. But so far the sensitivity of the tactile elements has not been sufficient enough to meet the imposed requirements. In prior projects we considered to achieve a TRL 6 of the tactile gripper. Scape Technologies already has a TRL 9 since they brought the bin-picking system into a real industrial application.

In the following, we are going to explain, how we are able to achieve a TRL 7 for the bin-picking application with regard to the tactile gripper.

# TRL Evaluation

**Following TRL Explanation is taken from the Multi-Annual Roadmap:**

**Level 1 - Basic Principles Observed**

Idea: Basic technology research.

Document elaborated which describes a product / feature idea and/or potential market

requirement: Functional description, customer benefit, ideas for realisation.

Yes.

**Level 2 - Technology Concept Formulated**

Concept Formation: Basic technology research.

Proof of principle developments including algorithm development and simulations.

Concept formulated with details on potential development risks, including coarse

resource planning.

Yes.

**Level 3 - Experimental Proof of Concept**

Experimental Development: Technology development.

Realisation of parts of the Concept to visualise the product / feature idea; proof of

concepts, first components and interfaces developed; lab experiments carried out; future

technical scope of work identified

Yes.

**Level 4 Technology Validated in Laboratory**

Experiment: Technology development.

Testing of system or major sub-systems; validation against established benchmarks;

Testing of internal and external interconnectivity

Yes.

**Level 5 Technology Validated in Relevant Environment**

Lab prototype: Internal technology demonstration.

Main functionality of product / feature idea can be demonstrated.

Major risks for the realisation of a future product / feature have been documented as part

of the description of the Demonstrator / realisation.

Yes.

**Level 6 - Technology Demonstrated in Relevant Environment**

Functional model/First Field Trials: External technology demonstration.

Main functionality of a of product / feature idea is realised at a degree that selected

customers can carry out tests, when accompanied by developers.

Yes.

**Level 7 - System Prototype Demonstration in Operational Environment**

Engineering Prototype

Development of prototypes with final technology subsystems or close analogues in a

close to complete form factor.

All identified functionality is capable of being demonstrated.

Customer verification trials (independent of developer support) possible.

Yes, see pickit experiment.

**Level 8 - System Complete and Qualified**

Production Prototype

Development of prototypes with final functionality and form factor.

Sufficient for end user testing in limited launch markets.

Initial batch production of the products.

No

**Level 9 - Actual System Proven in Operational Environment**

Series production and sales.

Going further, it is possible to formulate questions related to TRL for a more rigorous verification, whether the TRL has been reached.

**TRL 1: Have basic principles been observed and reported?**

**Scale Comments**

Has a reasonable process concept been proposed?

***Yes, the basic principle of piezoresistive sensors and our multi-modal system have been* *explained among others in our patent regarding the matrix structure of the piezoresistive sensor elements.***

Do basic principles (physical etc.) support the concept?

***The basic principle includes applying a force on the sensor, which as a consequence creates more conductive paths resulting in higher local conductivity. The reason here, is that the conductivity increases locally because of the local resistance decreasing.***

Have scientific observations been reported?

***In our paper “Sensor Calibration of Piezoresistive Material” we described among others the effect and conductivity principle behind that effect. Nevertheless in the TAKSENS project we have done a lot more deeper investigation.***

Have mathematical formulations of concepts been developed?

***There are many different approaches utilized describing the working principle of piezoresistive sensors. Conductivity principles include among others the “tunnel effect” or creation of conductive paths by applying pressure on the sensor.***

Do rough calculations support the concept?

***Calculation of the piezoresistive effect have not been reported sufficiently so far since every piezoresistive material has slightly different material properties e.g. concentration, shape and kind of conductive particles in different polymers, which result in different effects. In the bachelorthesis “Entwicklung und Validierung taktiler Sensoren für verschiedene Greifer “ we have experimental quantized the effect of drift, hysteresis, force dependency and area dependency applied forces.***

**TRL 2: Has a concept or application been formulated?**

**Scale Comments**

The concept of the piezoresistive sensor is widely explored and descirbes the effect of placing electrodes above and underneath piezoresistive material. When using many lines of electrodes, the crossing areas are finally arranged as sensor matrix. When electrodes are placed underneath and on top of the pr.-material they cross each other and define a specific sensor cell. When a voltage is connected between two crossing stripes of electrodes a certain rest current is defined which increases due to pressure applied to the sensor.

The application process of our multi-modal bin-picking system is described in D.4 of the *pickit* experiment. The basic idea using the sensor is the validation of grips through force distributed pressure or to even locate an object singularly based on the tactile feedback.

Have functional requirements been determined? ***In the TAKSENS project, we have done investigations on the sensor design and material including the investigation on the working principle and physical dependencies.***

Have results of analytical studies been reported in peer- reviewed papers?

***Our paper “Sensor Design and Calibration of Piezoresistive Composite Material” has been peer review before being published and presented at the IEEE Sensors 2015. Furthermore, we have found several scientific publication concerning about this issue as well and supporting our paper.***

Have potential design solutions been identified?

***Yes. In regard to the magnet gripper we tested different cover layers and designs on different mounting points. From our tests we considered to place the tactile sensor on top of the magnet gripper, since the magnet force is still sufficient to grip the parts. For the suction cup we did this alike.***

Have the basic components of the technology been identified and partially characterized?

***Yes. We have tested different electrode materials and piezoresistive materials, determining impact of varying temperature, force, area of interaction to choose the most promising material here, mainly in respect to attain max. sensitivity and temperature sustainability.***

Has preliminary qualitative risk analysis been documented?

***Risks of this technology are documented in the TAKSENS project. One great advantage of the sensor concept is, that it self-monitoring since the sensor output for a valid sensor is still above 0.***

**TRL 3: Has analytical and experimental proof-of-concept been demonstrated in a laboratory environment?**

**Scale Question Comments**

In the TAKSENS project we have confirmed the working principle of the tactile sensor technology. Furthermore, we have several demonstrators representing the use of tactile sensor in true environmental condition. Also the tactile sensors for the grippers are used in true environmental conditions.

Have experiments validated the predicted capability of technology components?

***We have conducted several experiments on the sensor, determining and quantifying effects of hysteresis, drift, force and area dependency of the tactile sensor. Results are presented in the paper “Sensor Design and Calibration of Piezoresistive Composite Material”, in the TAKSENS report as well as in the bachelor thesis of Mr. Long. regarding “Entwicklung und Validierung taktiler Sensoren für verschiedene Greifer”***

Are the technology or system performance metrics established?

***The sensitivity of the sensor can be adapted through parametric adjustments of the sensor controller. This allows to adequately establish the measuring range of the sensor. Adaption of controller parameters, especially with regard to adjustment of sensor sensitivity is necessary since different force measuring ranges apply for different gripper e.g. the magnet gripper achieves force above 80N whereas the suction cup gripper is leveled at 10N. Further adjustments regarding drift correction based on parametric adjustments can be utilized.***

Can science relevant to developing the technology be modeled or simulated?

***The modelling of the sensor features is rather difficult since many different dependencies need to be taken into consideration. A literature research has shown that there is no satisfying model of the sensor till now.***

Have technology or system performance characteristics been confirmed and documented with representative data sets? ***See also TAKSENS, “Sensor Design and Calibration of Piezoresistive Composite Material”, Bachelorthesis Mr. Lam***

Do the results of technical application experiments verify the feasibility of such applications? ***Since attachment of the sensor to the grippers in Jan 2016 the sensor has not been damaged or ripped of the grippers. The algorithm implemented still works for the same application.***

Does published research provide evidence for successful integration of technology and system components? ***Yes, see among others our publication regarding “VALERI - A collaborative mobile manipulator for aerospace production” and a” A new Multi-Modal Approach towards reliable Bin-Picking***

***Application” etc.***

Have design techniques been identified and/or developed? ***Yes, we have used different fabrication methods on different application requierements. Whereas the tactile floor mat, uses different electrode, design and structure, the tactile sensor for grippers consists of a much more higher sensor resolution.***

Have scaling studies been initiated? ***We used the tactile sensor on a magnet gripper consisting of less spatial sensor resolution than the sensor used for the suction cup. Furthermore the size of the sensor array and the size of the sensor cells varies here.***

**TRL 4: Has prototype-scale testing of equipment been completed in a laboratory environment?**

**Scale Question Comments**

Have system requirements been finalized and documented? ***Yes, this was one of the main issues in the bachelor thesis of Mr. Lam and among others was published in the paper regarding “A new Multi-Modal Approach towards reliable Bin-Picking”. All results are recorded and documented.***

Have design requirements been derived from system requirements? ***Yes. In order to detect objects with the tactile sensor the sensitivity as well as the spatial resolution as well as the size of a sensor element need to be adapted.***

Have system performance metrics been updated? ***Due to different choice of materials (piezoresistive material and electrode material), the sensor properties may also vary. We have tested different material combination thus leading to different sensor properties. The performance data has been updated for the current material combination and recorded alike.***

Have scalable technology prototypes been produced? ***Tactile sensors for rigid structures and flexible structures and with high spatial resolution arranged radially or in a matrix with different coverings, preventing the sensor from harm, have been manufactured and tested.***

Has the performance of components been demonstrated at lab-scale? ***Before the gripper has been used in real application, we tested the magnet gripper placing parts on various gripper areas while using the same part detection/recognition algorithm.***

Have performance characteristics of a lab-scale prototype been demonstrated? ***Yes, we have tested the sensor pressurizing all sensor cells homogenously. Then we increased the pressure on the sensor. From the experimental results we derive a sensor feedback allowing the validation of a proper operating sensor. Furthermore, the sensor worked properly over the complete runtime of the experiment.***

Have low-fidelity assessments of system integration and engineering been completed? ***The sensor has been attached to the appropriated grippers. The software protocol which is responsible for reading out the sensor data has been used during the complete runtime of the pickit experiment and has proven to be robust in real application environment. Although, the engineering of the sensor design needs to be improved in terms of feasibility since the sensor can be ripped of easily from other parts, which have a thinner contour than the parts used so far.***

Have materials, processes, methods, and design techniques been identified? ***We have done large scale investigations on different materials (electrodes, piezoresistive material) and assessed a certain material combination to be most promising. We have used different fabrication methods and sensor designs (radial, matrix arrangement of sensor cells) to test our sensor in different application context.***

Are most system components available (laboratory surrogates in some cases)? ***Yes, all sensor components are available on the market.***

Have initial cost drivers been identified***? In the Bmbf TAKSENS project we have done an overall study on the costs of the sensor to cover a complete robot. This can be adapted for the tactile sensor attached to the grippers alike.***

Has analysis of alternatives been completed? ***We also use capacitive sensors for certain applications. These sensors often lack in terms of robustness and reproducibility and thus are less appropriate for safety issues. Tekscan sensors use different sensor fabrication methods, which often suffer from less robustness and less flexibility. Analysis on different sensor technologies (inductive, capacitive, piezoresistive, piezoelectrical etc.) have been done in a large scale by different people.***

Have programmatic risks been identified and mitigation strategies been documented? ***Yes. Also in the realm of the TAKSENS project our sensor technology has been investigated thoughtfully. The tactie sensor sometimes suffers from less accuracy mainly when it comes to large area coverage.***

**TRL 5: Has pilot-scale testing been demonstrated in a relevant environment?**

**Scale Question Comments**

Have system interface (internal and external) requirements been documented? ***Yes.***

Does the pilot operate under realistic conditions? (here further specifications of what “realistic” means for the given application) ***Yes, since the system operates in a realistic bin-picking application, by means gripping angle tubes and washers we could successfully demonstrate our tactile sensor in a multi-modal sensor approach. We can call every desirable bin-picking application operation in real environment a “realistic” scenario testing.***

Have individual components been verified and validated through testing? ***The tactile sensor, used for both grippers has been tested in real operational environment by means the robot position has been calibrated according to the object position in the tactile gripper. Also, the determination of object situation in the gripper has been successfully tested. All tactile sensor elements so far have been validated as well.***

Has integration of modules/functions been demonstrated in a laboratory environment? ***Yes, we first tested the tactile sensors in a laboratory environment including e.g. placing the washers in different part poses in the tactile gripper in order to verify whether the part pose can be determined successfully. From this, we attain a tactile feedback, which is similar to the feedback under realistic environmental conditions.***

Has system process design been finalized? ***Yes, the design of tactile sensors including the electronic design, the attachment of the sensors to different gripper shapes and structures (suction cup, magnet gripper, two-finger gripper), the implementation of program code into existing process structure of a common bin-picking system have all been finalized.***

Has systems engineering begun? ***Yes, we have already attached the tactile sensor array to the grippers and introduced the software algorithm into a realistic operational environment. Although, the system software algorithm needs to be incorporated into existing bin-picking systems to make it much more feasible and robust using different shaped parts.***

Has a configuration management plan been documented and implemented? ***Yes. Scape uses a Configuration Manager especially designed for setting-up the system including all relevant components like camera, grippers, projection light. We made a short overview on how to set-up the multi-modal system. This gives a chronicle order of starting programs and testing and calibration of all components.***

Has formal review of all documentation been completed? ***No, not all documents have been reviewed so far due to some legal aspects.***

Are materials, processes, methods, and design techniques at least moderately developed and verified? ***Yes, all materials have been tested and the results been recorded. The processes have been utilized and verified and the fabrication method has been documented. The design process has been used on different kinds of sensors.***

**TRL 6: Has prototype (semi-works pilot) engineering scale testing been demonstrated in a relevant environment?**

**Scale Question Comments**

Have system integration issues been addressed? ***Yes, our sensor device can be used in different application areas using mainly USB or after reconfiguration of read-out protocol with Ethernet. The tactile sensor can be attached to different grippers as we demonstrated so far.***

Is the operational environment fully known and documented? ***Yes, the bin-picking system of Scape Technologies fulfils the standards of TRL 9, which includes a proper documentation, process of system relevant characteristics.***

Has prototype been tested in real operating environment? Can customers carry out tests (when accompanied by developers)? ***Currently, we integrated the tactile sensor technology into a real bin-picking application. This allows us to verify the correct part pose in the gripper. Whenever a costumer likes to carry out tests with the sensor, he can purchase one from us.***

Are the components of the pilot functionally compatible in realistic problem-solving tests? ***Yes, we tested the algorithms regarding detection of part grip, part drop etc. The results have given evidence on the usability of tactile sensors in bin-picking. Although, we used a matlab program here, which might be not used in real industrial application.***

Has engineering feasibility been fully demonstrated? ***We have conducted several tests with the tactile sensor attached to the grippers. From the tests, we derive adequate sensor data covering the complete measurement range.***

Has collection of maintainability, reliability, and supportability data started? ***In the paper ”A new Multi-Modal Approach towards reliable Bin-Picking Application” we inform about the reliability of the multi-modal bin-picking system in regard to gripping the part accurately. The maintainability is given from the functionality of the sensor which had not to be replaced till now but can be easily fabricated and replaced.***

Has the final technical report been completed? ***We worked out a technical report on the complete pickit experiment (final report of the pickit experiment). We included different aspect of scientific results.***

**TRL 7: Has equipment/process successfully operated in the relevant operational environment?**

**Scale Question Comments**

Has process equipment been tested individually under stressed and anomalous conditions? ***We have tested the tactile sensor from gripping washers with about 80N attraction force by the magnet gripper and holding the part in the gripper for about one week. The tactile sensor for the suction cup was pressurized constantly as well, by bringing it in an anomalous positon after shutting down the robot. Finally, we can outline that the tactile sensors were attached to different grippers (suction cup and magnet gripper) in Jan 2016, till then, we did not need to repair for the sensors.***

Has operational testing of the process in relevant environment been completed? ***We tested and used the tactile sensor at our technical center and demonstrated our approach at the Automatica for two different grippers on two different parts, namely washers and angle tubes. The suction cup has also been utilized for the identification of objects through use of sequential contact forces.***

Is data for Reliability, Maintainability, and Supportability analysis available? ***As explained before, we have tested all material properties like electrodes and piezoresistive material, separately and in induvial combination. The results of our experimental test bench can be seen in our paper “Sensor Calibration of Piezoresistive material”.***

Are process equipment and materials available? ***All necessary materials for fabrication, manufacturing and use of the tactile sensor arrays are currently available on the market and at our facility.***

Do prototypes represent actual form, fit, and function? ***Yes, we can build a tactile sensor for the magnet gripper and the suction cup. Whenever necessary, the form, size and number of sensor cells can be changed. The functionality is given:***

|  |  |  |
| --- | --- | --- |
| ***Requirements*** | ***Magnet Gripper*** | ***Suction cup*** |
| ***Measurement range*** | ***2…80N*** | ***2…10N*** |
| ***Form*** | ***radially arranged*** | ***Radially with hole in the middle*** |
| ***Necessary spatial sensor resolution for measurement of*** | ***About 2mm*** | ***Considering one column with 16 sensor elements on a radius of 18mm*** |
| ***Functionality*** | ***Measuring the pressure distribution to detect object orientation and location, part drop and successful grip*** | ***Detect exact part position when part is gripped (Unfortunately the accuracy is a bit low, which prevents the sensor to be used till now.in industrial application)*** |

Have software algorithms been verified and validated with existing systems? ***As described in our paper ”A new Multi-Modal Approach towards reliable Bin-Picking Application” we have successfully tested our multi-modal approach against the existing bin-picking approach, which solely depends on camera data. This was done in respect to the cycle time of the system. While the common approach is a bit more reliable till now, it seems that our approach is sufficient for the existing application though.***

Is scaling completed? ***We have designed the tactile sensors starting at a spatial resolution of about 4mm and going up to 2mm (and even up to 1 mm, but the sensor suffers from cross talk). They can cover complete areas like flat rigid areas (magnet gripper) or can be attached to flexible structures like a suction cup. They can be realized as sensor matrix (two finger gripper) or can be radially (suction cup, magnet gripper) arranged, without affecting the functionality of the tactile sensor.***

**TRL 8: Has the actual unit successfully operated in a limited operational environment**

**No**

**Scale Question Comments**

Are all technology/system components form, fit, and function compatible?

Is technology/system form, fit, and function compatible with operational environment?

Has technology/system form, fit, and function been demonstrated in operational environment? (i.e. mechanical fixation of tactile sensor on robot)

Has technical Developmental Test and Evaluation (DT&E) documentation been completed?

Are all materials in production and readily available?

Has maintainability, reliability, and supportability data collection been completed?

Is maintenance documentation completed and under configuration control?

Have final architecture diagrams been completed?

Have software algorithms been verified and validated with existing systems?

**TRL 9: Has the actual unit successfully operated in the full operational environment (hot operations)?**

**Scale Question Comments**

Does technology/system function as defined in Operational Concept document?

Has technology/system been deployed in intended operational environment?

Has technology/system been fully demonstrated?

Has Operational Test and Evaluation (OT&E) been successfully completed and documented?

Have design to cost (DTC) goals been met?

Have safety/adverse effects issues been identified and mitigated?

Has all programmatic documentation been completed?

Has Certification PLd, Category 3 been reached for electronics?

Has an EC Type Test been carried out?