Eco2Painter

Economical and Ecological High Quality Painting at Highly Scalable Lotsizes

Project Co-ordinator: **PROFACTOR**

Partners:

AAU

AMROSE

ASIS

ATENSOR

FKI

INROPA

LACTEC

Publishable Final Activity Report

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Change History

Version	Date	Reason for Change	Pages Affected
0.1d	2007-09-12	Draft version	All
1.0r	2007-09-24	Release version	All

Summary description

European industry is in a transition from mass production industry towards a more competitive, knowledge-based, customer- and service-oriented one. Production on demand, mass customisation, rapid reaction to market changes and quick time-to-market of new products and variants at small batches are needed - at low cost and high quality Highly flexible, scaleable and user-friendly production equipment is needed, including robotic systems for **painting** – a common process in production.
The **necessity for the project rises from significant disadvantages of current automatic painting systems**, robotized as well as non-robotized ones. Within this project a new technology was developed which enables SMEs to customize efficiently and to rapidly and smoothly launch new products.
Eco2Painter aims at the development of a novel technology for self-programming painting robots that are capable of learning. Project results allow eco-efficient high-quality painting even of very small lot-sizes with downtimes during product changes that are 10-100 **times shorter than those of conventional systems**.
Within this project, a system was developed that uses sensors to reconstruct, recognize and decompose the products to be painted. Using this information, the process was automatically planned and robot programs were generated and executed subsequently. Quality improvements were achieved automatically or by ergonomic user interaction and were re-applied in planning future product variants The resulting improvements in the competitiveness will improve the Return of Investment (ROI) in eco-friendly painting-lines.

Strategic Objectives:

- Development of a prototype for a robotic painting-system that programs itself by use of active 3D-vision and a “what we see is what we paint” approach **at high quality**.
- Automatic “closed loop” application programming within **minutes instead of hours/days/weeks** for minimal downtimes at product changes and mixed production
- **Transferring knowledge and optimisations from one variant to the next**
- **Reduction of used paint** and increased quality
- Installation and field tests with demonstrator and preparation of exploitation of results

Project Objectives:

- Novel robotic system for flexible high-quality painting of highly scalable batch sizes. **Down-time due to product-changes** will be in the range of **seconds/minutes**, in comparison to downtimes or delays of conventional systems which are around hours/days/weeks.
- Retrofit a demonstrator into the robotic painting line of end-user FKI’s to perform real world evaluation and benchmarking against existing technology.
- Novel or radically improved system **components and tools**.
  - active 3D vision comprising reconstruction, recognition, localization, decomposition.
  - automatic paint process planner and motion planner for complex surface geometries
  - scheduler for creating near optimal multi-robot schedules (criteria: manual teach in)
  - for simulating the full application unveiling critical regions
  - for interactive and automatic (local) adaptation/optimisation of paint strokes

Knowledge and methodologies on **dealing with uncertainty and variance**

- through 3D localization, recognition and decomposition of complex 3D objects even for very large part variances.
- by novel (investigative) control of active range sensing, driven to retrieve missing information (geometrical uncertainties) and to reduce ambiguities of hypotheses.

Knowledge, methods and tools on **dealing with quality and efficiency** in automatic planning:

- through embracing automatic process/motion planning and simulation with adaptation / optimisation in a closed loop system and investigate convergence towards the criteria (quality, time, paint-usage) by iterative **optimization and learning functionality**
- through improved scheduling swapping tasks from one robot to another.

\- user interaction **dealing with workers and knowledge**:

by incorporating the worker`s expertise and experience for quality improvements without production downtimes by user interaction-tools using. process animation and evaluation.

Contractor List:

Participant name	**Country**	**Logo**
ATENSOR Engineering and System Technology GmbH&CoKG http://www.atensor.com	Austria	
LacTec Gesellschaft für moderne Lackiertechnik mbH http://www.lactec.de	Germany	
INROPA Aps http://www.inropa.dk/	Denmark	
AMROSE Robotics ApS (AMRO) http://www.amrose.dk/	Denmark	
ASIS GmbH (Automation Systems & Intelligent Solutions) http://www.asis-gmbh.net/	Germany	
FKI Logitex Crisplant a/s	Denmark	
Profactor Produktionsforschungs GmbH (PROFACTOR) www.profactor.at	Austria	
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1 Work performed

Eco2Painter enhances a “what you see is what you paint” approach. Efficiency is reached by automatic planning and flexibility is reached by sensing. Even completely unknown parts to be painted are (1) scanned while transported by the conveyor. (2) Next, the sensor information is interpreted and (3) used by planners to automatically plan paint strokes and robot motions. Next, the entire application is simulated (4) and the predicted painting result is used to control (5) either additional quality improvements or to execute the automatically generated programs on the robots (6). Quality improvements are done by (a) automatically adapting/optimising the paint strokes, or (b) by the operator interacting via an simple augmented graphical animation of the results and the planned strokes. Learning capabilities (supervised) allow a transfer of optimisations to next variants

The major innovation beyond state-of-the-art is clearly the novel system that efficiently paints products even at very small batch sizes at very high quality- with down-times near zero. Innovative features of ECO^{2}PAINTER are:

1. Robust active 3D sensing and recognition for large sets of parts and complex shapes.
2. “Closed loop” process and motion planning and scheduling.
3. Efficient interfaces for non-robotic experts.

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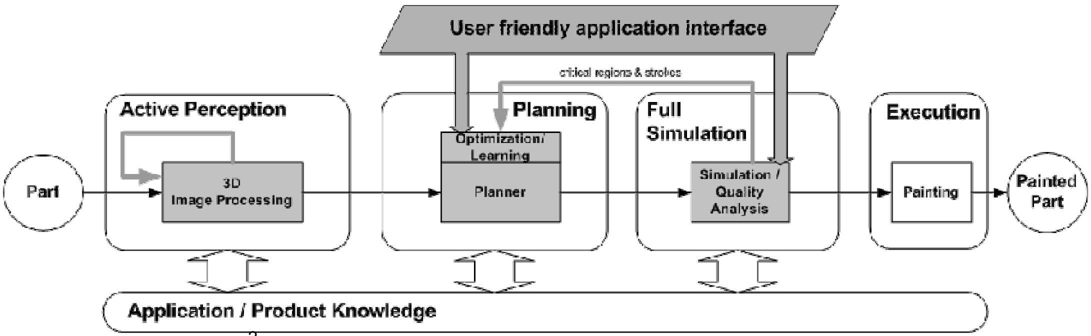


Sketch of the ECO^{2}PAINTER structure: From left to right: parts are perceived, the paint process and the robot motion are planned and – if sufficient – executed on the robot. Otherwise the automatic stroke adaptations and user input are fed into the planner for the next iteration

1.1 Robust active 3D sensing and recognition for large sets of parts and complex shapes

State of the art:

Intensity- or laser scanning based products used in production can localise only few parts with small pose deviations (e.g., ISRA, SIRA, OST), require manual teaching for any new part and do not deal well with variation of the sensing conditions (such as surface reflectivity). Latest developments combine different sensor modalities (colour, range) to improves discrimination power (e.g. cameras by IVP, EADS), but still suffer from robustness. **Research:** Huge progress in research on computer vision has been made within the field of autonomous robots, since these must deal with large variations of environmental conditions and complex environments. Cue integration, multi-sensor fusion, active systems showing attentive and investigative behaviours or cognitive vision have been active mayor research topics in the last years. The EU project VISATEC uses cognitive aspects for cue integration and adaptation to achieve robustness for basic robotic part localisation tasks.

Solution of Eco2Painter – Methology:

The perception system built in this project addresses a variety of topics in image processing from 3D data acquisition to 3D data interpretation.

Unlike 2D image processing the system is based on 3D imaging technology allowing accurate 3D data measurements for identifying and localization of products past through a production line.

As scenes in industrial environments are of high complexity traditional vision systems are constrained to well-defined tasks lacking adaptation and flexibility. To counter this issue a highly dynamic 3D vision system is required.

The concept foresees a full integration into the painting system. Goods to be processed are past through a flexible 3D sensor cell. In principle, the 3D imaging process is based on subsequent modules: (1) 3D data retrieval, (2) 3D reconstruction and (3) 3D data interpretation.

Figure 1: Workflow for perceptual routines

In order to retrieve accurate 3D information the system is based on a set of 3D sensors whose locations are automatically adapted to the true geometry of the goods to be scanned. According to the true geometry view points of the sensor systems are selected automatically. The sensor data of all cameras are filtered and registered over time to generate a full 3D model of the product. In order to align data from different cameras in an industrial setting sophisticated calibration and registration procedures have been developed to set up a 3D sensor system at minimum time.
Having retrieved a full 3D sensor dataset a reconstruction procedure of the underlying surface is required. There have been numerous algorithms developed over the last years tackling the problem of surface reconstruction. Considering the fact that an industrial setting implies vibrations, ambient light, reflections, which renders a surface being far from smoothness and connectivity, an adaptive 3D mesh triangulation algorithm has been adopted based on the marching triangulation principle.

A conditioned 3D dataset in form of reconstructed 3D surface patches provides rich topological 3D information such as surface orientation and curvatures. That kind of information is used to feed the 3D object recognition routine. Recognition in the sense of the proposed system means interpreting 3D data in the context of provided CAD database of the product range. Generally the recognition task is considered as matching task between two surfaces. The proposed 3D object recognition scheme is based on shape signatures which do not impose a parametric representation on the data, so they are able to represent surfaces of general shape.

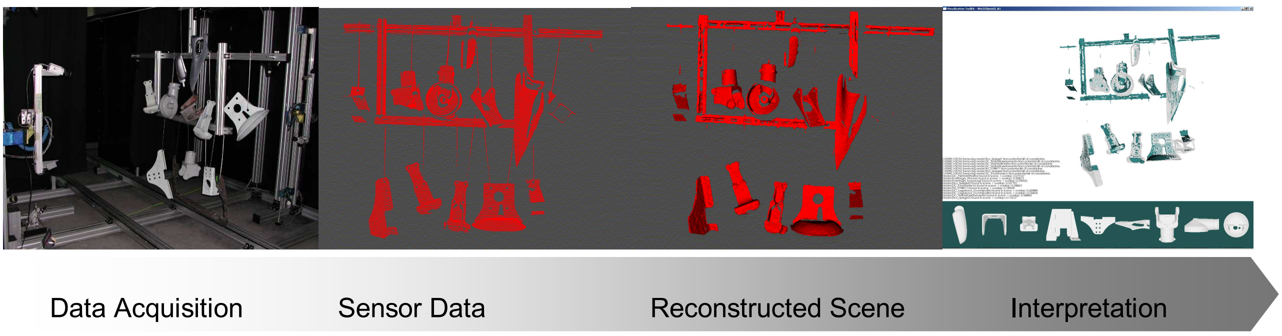


Figure 2: 3D Imaging: (From left to right) Sensor acquisition from parts to be painted, sensor data consisting of 3D points, reconstructed data as result of the triangulation meshing procedure, interpreted scene labelling reconstructed data with proper CAD IDs.

Results:

As a result, a SW tool for accurate 3D position/orientation determination, based on algorithms provided as background has been developed. The prototype tool is able to localize complex objects/parts robustly even if strong occlusion (e.g. by overlapping parts) appears. PRO developed mathematical methods to recognize complex shaped 3D objects in an industrial setting. These implemented methods were tested in the laboratory as well as in the production plants of the SME end user where there is much of clutter, occlusions and background noise. The system demonstrates robust active scanning with high robustness against part-motion and poor surface conditions. A simple user interface allows setting up the system in an intuitive way.

1.2 "Closed loop" process and motion planning and scheduling

State of the art:

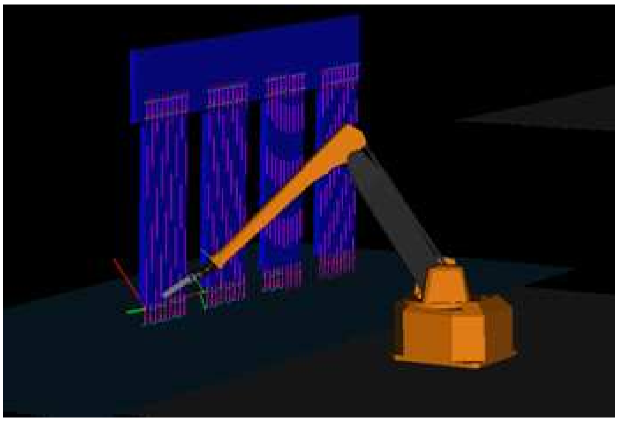
Agile robotic systems for painting also small batch-sizes have only been presented by the 5'th framework project FlexPaint so far. In FlexPaint, automatic programming of painting robots was enabled for the first time. The automatic programming is based on 2 distinct features, which are extracted from a geometry model of the object to be painted. The geometry model is created by scanning the object by laser-profiling sensors. Then the shape is reconstructed and concavities are detected. Next, the paint planning is using the surface representation and the features separately to plan the process. The motion planner then separately calculates the paths of the robot and generates a program to be executed.
As capital investments in painting plants are considerable, overcoming the inherent limitations in paint quality and speed or time to production of the FlexPaint system would boosts its impact.
Other approaches such as the CMU's deposition model based paint planning focus on advanced spray-modelling in order to reach the quality, but are still behind the European State of Art concerning the automatic planning.
The Smart-Painter project aims at CAD based painting. Automatic generation of paths has been attempted by virtually un-folding surfaces to be painted, mapping paint strokes and then folding back the surfaces and strokes. The approach is limited to parts of low surface curvatures and does not integrate sensory information.

Solution of Eco2Painter – Methology:

Designing a closed loop process encompassing a collision free motion planning and scheduling addresses the development and advance of several key-features:

- Development of automatic Painting Process Planner
- Simulation of the full process unveiling critical regions
- Adaptation / Optimization of automatically generated paint strokes

The automatic paint process planner allows generating a process plan for non-flat surfaces using flexible stroke types. This has been particularly developed for convex shaped parts. Advanced methods for specification of path smoothness and process angles for paint tool have been developed by taking into account control points and path directions during angle specification. Furthermore unnecessary strokes and overspray can be discovered through light process simulation which simulates a normalized coverage of the parts without any special effects, such as e.g. electrostatics. Slightly curved surfaces can be painted by using control points in paint strokes directly in the automatic process planning. Optimization of paint process is achieved by forcing directions of paint motions and paint strokes. The integraed motion planner resorts to an optimized kinematic modeling to reduce computation time to 50% allowing parts to arrive more frequently. Tasks can be specified with "Soft task constraints" allowing the path planner to deviate from the specified (optimal) path, thereby allowing the robot to perform paint strokes that would otherwise be unreachable or in collision. Therefore reachaility and coverage are improved.



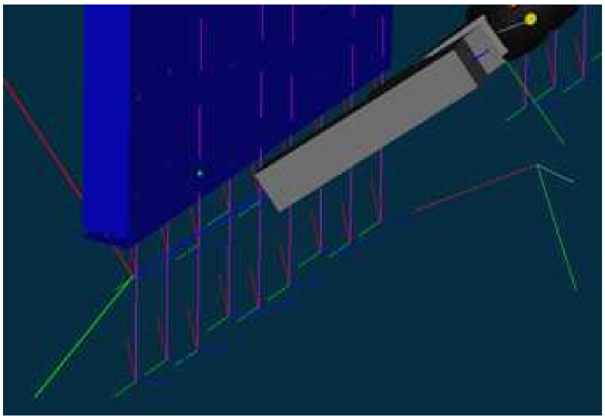


Figure 3: Robot reaching paint stroke outside the work envelope by deviating from the specified orientation.

A Scheduler for creating near optimal multi-robot schedules has been further developed and implemented. It has been closely integrated with the motion planner. Robot joint angles are included in objective function.The scheduler can choose between several joint configurations for each paint stroke (if more than one exists) Quality rules are included in the scheduling rules (grouping)Deleted strokes are redistributed to a new robot and the task is rescheduled. Furthermore the scheduler is integrated with the new InropaBasic 3.0. Having integrated this kind of novel scheduling (1) the total painting time is close to optimal (minimal), (2) a satisfactory painting quality is obtained, (3) the number of automatically planned collision free paint strokes is maximized and (4) the computation time is minimized.

The evaluation and interpretation of the possible paint results caused by the generated paint strokes requires a simulation based on a well-defined paint model. A simulator unveiling critical regions has been developed. It is basically a tool to evaluate the quality of the generated robot program. It can be accessed via an intuitive API which accepts paint-strokes from Inropa-Basic as Inputs. A slider controls the trade-off between quality and speed of the simulation. The result of the simulator is the relative paint-thickness for the entire workpiece. This information can be used to decide on whether to replan or optimize the paint-strokes. And this is the point where the process loop is getting closed.

Based on the simulation results the paint strokes are adapted or optimized either by a human operator using the manual editor or a novel automatic optimization procedure. Optimizing paint strokes requires a robust optimization method bound to the following requirements:

- Support for dynamic environments
- Robust against local minima of the fitness function
- Optimization has to be based on coverage simulator results

The best suited approach for the above requirements has turned out to be a particle (swarm based) approach. A multi purpose framework for optimization with particle swarms has been adapted for the Eco2Painter project. Particle swarms are based on the food searching behaviour of flocks (e.g. fish schools or birds), and is a simple yet robust and fast optimization methods. The framework has the ability to optimize multiple continuous parameters at once, and is able to track the optimum of fitness functions that vary over time.

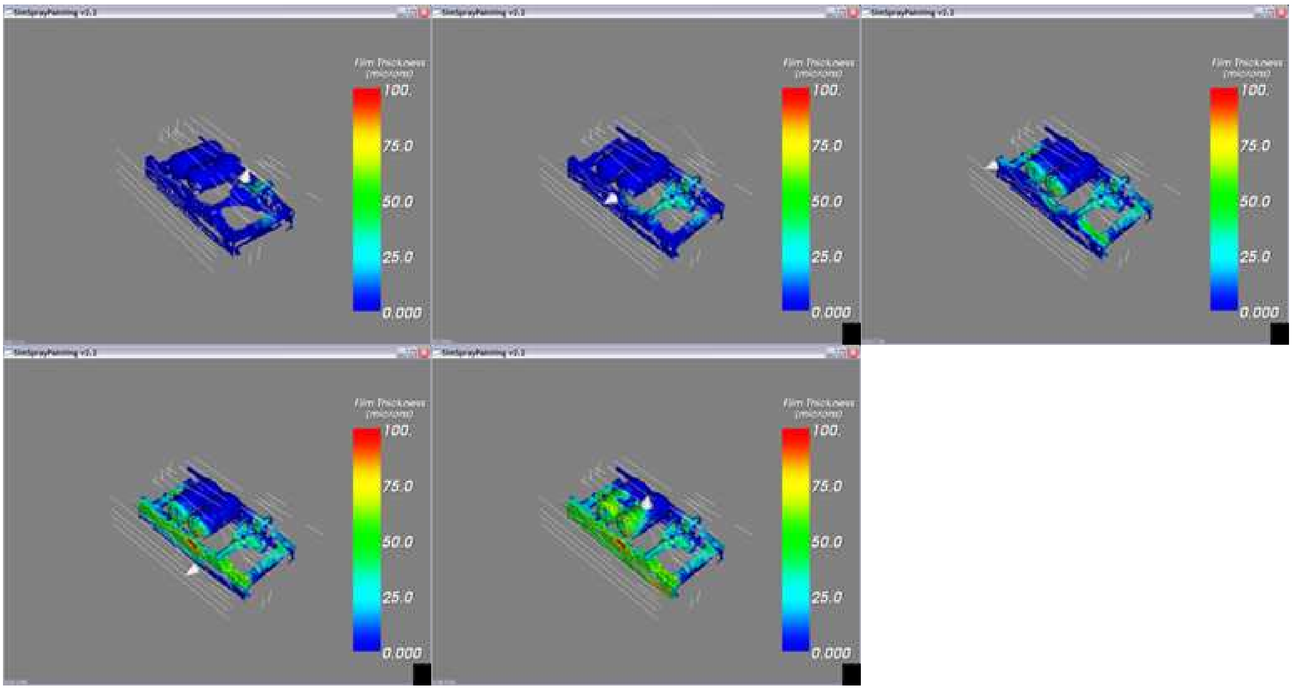


Figure 4: Simulation of automatically generated paint strokes

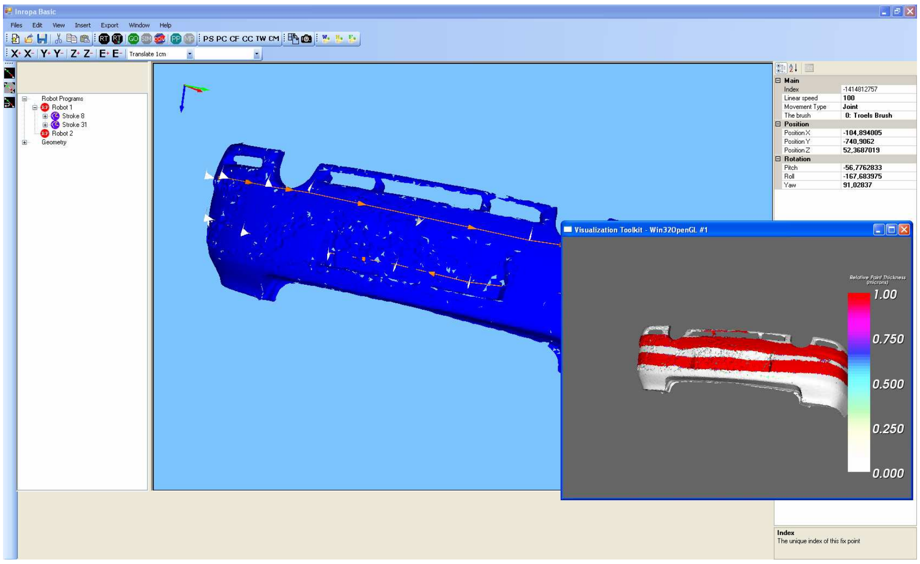


Figure 5: Integration of simulation tool in paint planning software

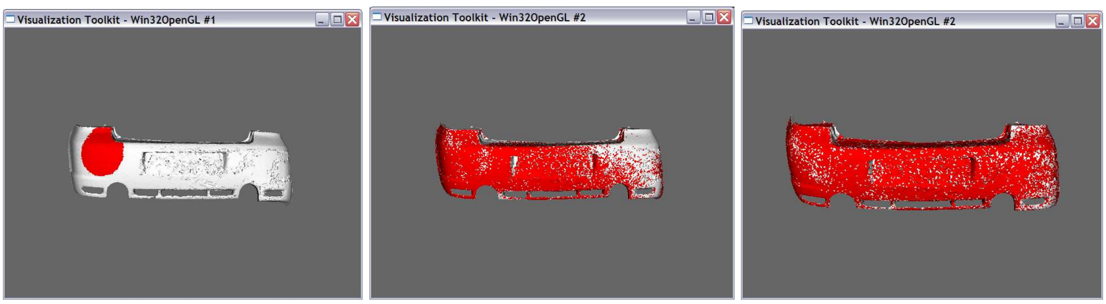


Figure 6: From left to right: (a) Initial scenario. 25 process points roughly initialized to the same position. (b) Optimization after 10 iterations (coverage 65%). (c) Optimization after 30 iterations (coverage 89%).

Results:

In order to enable a closed loop process a variety of distinguishable methods have been developed, implanted and integrated in a common framework.

- Automatic paint process planner and motion planner for complex surface geometries featuring
    - Possibility to use flexible stroke types on non-flat surfaces.
    - Advanced methods for specification of path smoothness and process angles for paint tool.
    - Light process simulation to discover unnecessary strokes and overspray.
    - Possibility to specify defined painting directions for decomposed parts with known normal directions.
    - Possibility to force directions of paint motions according to cell specific painting directions.
    - Possibility to force directions of paint strokes according to part directions.
    - Enabling painting of slightly curved surfaces using control points in paint strokes directly in the automatic process planning.
    - API allowing close integration and advanced communication between paint planning-, scheduling- and path planning software
    - Tasks can be specified with "Soft task constraints" allowing the path planner to deviate from the specified (optimal) path.
- A novel scheduler has been developed which has been closely integrated with the motion planner.
- A paint simulator for unveiling critical regions
- An Optimization / adaptation procedure to optimize generated paint strokes

1.3 Efficient interfaces for non-robotic experts

State of the art:

Important pioneering work has been performed within the EU-projects NOMAD – presenting CAD-based welding and AUTOFETT – flexible off-line automatic fettling. The CRAFT project FIBRESCOPE demonstrated robots for small batch size inspection employing CAD-based user interaction and automatic program generation within 2-10 minutes.

Solution of Eco2Painter – Methology:

The development of an efficient interface for non-robotic experts required a close cooperation with the manual painters integrating them seamlessly into the Eco2Painter system. An intuitive user interface allowing to take control of the Eco2Painter system and giving them the impression to plan the paint process on their own is of much importance.

Beside having enhanced the InropaBasic which basically generates paint strokes, with sophisticated stroke editing tools a user assisted process tool has been implemented. To create a user assisted process optimization tool a novel approach has been taken. This approach is uses CAD models in a Virtual Reality Human Machine Interface. The fundamental idea behind the solution was to create an offline programming tool for paint robots, which would make it possible to create robot programs both faster than using the teach-panel and offline. The system should focus more on painting knowledge than on robot- or computer knowledge. Finally it was desired to make the system robot brand independent.

It was decided to base the system on Inropa Basic. Which was to be used to load work pieces and translate the robot program to any given robot language. The system is referred to as RobTeach VR.

System Setup

It was desired to create a system which would be as similar to painting normally using a spray gun as possible. As a consequence a CAD-augmented VR system has been created. In this system the user stands in front of a screen, onto which a CAD model is projected. The projection is performed using stereo graphics and when wearing 3D-glasses it is possible to make the CAD-model appear as if being in front of the screen. As an offline programming system was desired another mean than using the actual robot was required. To keep the system as close to using a real spray gun a pistol has been created. The created pistol and glasses are shown in Figure 7.

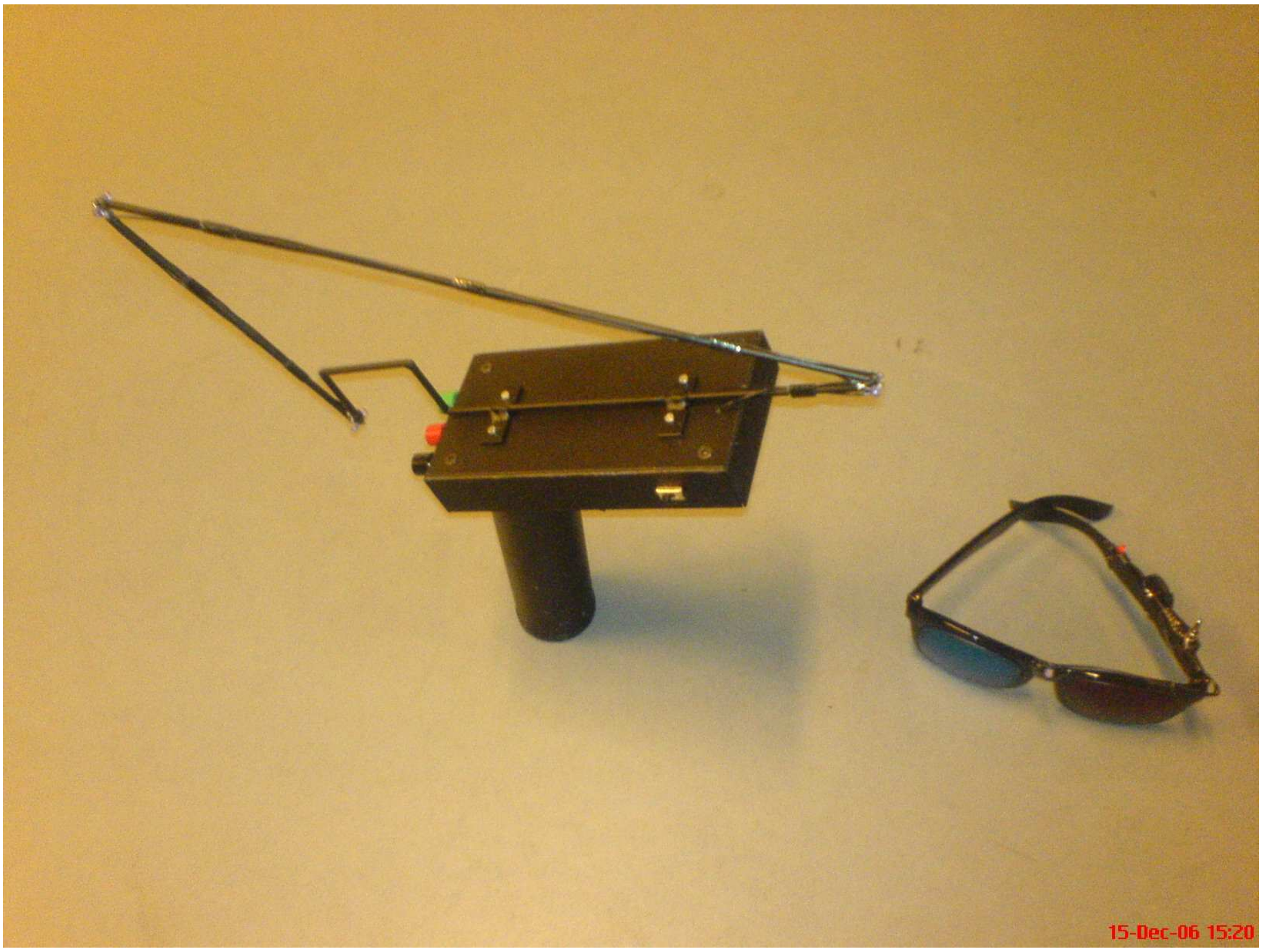


Figure 7: Pistol and Glasses

Using the pistol and glasses the user is to stand in front of a screen onto which a stereo graphic projection is created. There are four buttons on the pistol of which three are used. The button must commonly used is positioned at by the index finger when holding the pistol. The remaining three are positioned at the end of the pistol as seen in Figure 8. The two buttons on the back which are currently in use are the green and red one. The functionality of the buttons is explained in the following.

Figure 8: System Setup

In order to make the system able to register the pose of the pistol a tracking system has been created. This tracking system utilizes infrared light to track the pistol. To make the user capable of moving around the CAD-model the glasses are similarly tracked. The augmented CAD-model is thus manipulated according to the users position which makes it appear stationary in space as the user moves around. To aid the user in determining where the TCP is according to the pistol, a virtual TCP is rendered and moves as the pistol is moved.

Results:

An efficient interface for non-robotic experts has been developed featuring

- Improved InropaBasic allowing flexible editing of paint strokes
- 3D-virtual reality technology developed at AAU has been integrated with the Inropa™ Basic program The resulting system (RobTeach) removes the need for robot know-how in the programming phase

2 Publishable results of the final plan for using and disseminating the knowledge

2.1 A self-programming robotic system for painting at small lots

Description:

HW-SW solution that programs painting robots automatically. HW is placed in front of a regular painting booth or along the conveyor that transports the parts to the painting cell. It includes:

- A 3D sensor-recognition system to scan racks including parts and recognizes the parts and their pose in the rack (by use of CAD information).
- A SW-Tool-Chain that plans the painting process and the robot strokes and schedules and collision free robot motions. Finally the robot code is generated and uploaded to the robots and executed when the rack reaches the painting booth.

The generation of the programs requires minutes depending on the complexity of parts that can range up to 15 meters length. It is especially capable for painting at very small lot-sizes or one-of-a kind jobs since the programming is automatic. The downtimes for changing parts is zero if the system is positioned in sufficient distance in front of the paint booth (dist > computation-time*conveyor-speed).

Market applications:

The system is the extension of a proceeding system (installed and operating) towards higher quality painting and new use cases. A new version with first improvements will be available autumn 2007 as complete systems with robots or as retrofit.

Stage of development:

The algorithms have been tested and parts of the developed modules have been adapted and integrated for customer projects.

Collaboration sought:

Licensing agreement

Collaborator details:

Companies in the field of robotics, sensors and system integrators are interested in adapting the developed small lot size technology for their purpose.

Contact details:

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2.2 A tool for automatic planning of robotic paint processes with flexible strokes

Description:

The results are improvements and extensions of an existing paint process planner by use of flexible paint strokes where before only paint linear strokes where considered. The results improve the quality and the applicability reached by use of this tool.

The results are embedded in an Offline / On-line PC-based Software Tool for automatic CAD-based planning of the painting process and the necessary robot paint-strokes and schedules for one or more painting robots.

Linked with a motion planner (standard version of the Tool when shipped), the executable code for the robots is generated to be uploaded.

Market applications:
The results are already integrated in a SW tool that is already marketed towards higher quality painting jobs and wider range of use cases. The product-version that includes these improvements will be available in autumn 2007.

Stage of development:
The algorithms have been tested and parts of the developed modules have been adapted and integrated for customer projects.

Collaboration sought:
Licensing agreement

Collaborator details:
Companies in the field of robotics, sensors and system integrators are interested in adapting the developed small lot size technology for their purpose.

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2.3 A tool for collision-free motion planning with shared Degree of Freedom

Description:
The results are new algorithms that improve an existing robot motion planner by sharing the allowed tolerances of the robot motions (defined by the process) and the relevant degree of freedom. This allows for planning (finding solutions) of collision free executable motions in more dense structured environments (more obstacles or more complex parts that limit the free space for the robot).
The results extend the range of use of the existing (Offline/On-line PC-based) Software Tool for automatic motion planning. The tool can plan motions independent of the process and the source of the input trajectories (OLP, automatic planner, a.s.o) for which to find executable motions.

Market applications:
The results are tested integrated in a SW tool that is already marketed since 2002. The product-version that includes these improvements will be available in autumn 2007.

Stage of development:
The algorithms have been tested and parts of the developed modules have been adapted and integrated for customer projects.

Collaboration sought:
Licensing agreement

Collaborator details:

Companies in the field of robotics, sensors and system integrators are interested in adapting the developed small lot size technology for their purpose.

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DK-5230 Odense

2.4 A SW module for fast simulation of non-contact processes

Description:
The result is a SW module that is able to rapidly simulate the effect of different non-contact processes on the processed parts, given the process relevant tool motions. It than can analyse the effect and identify regions that are not optimally treated. It can be used for robotic and non robotic applications.

Market applications:
The module exist as prototype SW code and would be ready to market 01.01. 2008.

Stage of development:
The algorithms have been tested and parts of the developed modules have been adapted and integrated for customer projects.

Collaboration sought:
Licensing agreement

Collaborator details:
Companies in the field of robotics, sensors and system integrators are interested in adapting the developed small lot size technology for their purpose.

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2.5 An active profiling-based 3D vision system for reconstructing part shapes

Description:
The result is an enhanced 3D vision system that actively scans by use of a profiling sensors surface of a parts for the purpose of reconstructing or re-engineering the part shape. The system can be built up of several active controlled and co-ordinated sensors in order to scan the entire surface of the part (from all relevant sides). Data of the different sensors can be merged into a coherent model of the part.

The system has a variable sensing range and can scan parts up to several meter.

Market applications:
The results are already integrated in a SW tool that is already marketed towards higher quality painting jobs and wider range of use cases. The product-version that includes these improvements will be available in autumn 2007.

Stage of development:
The algorithms have been tested and parts of the developed modules have been adapted and integrated for customer projects.

Collaboration sought:
Licensing agreement

Collaborator details:
Companies in the field of robotics, sensors and system integrators are interested in adapting the developed small lot size technology for their purpose.

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2.6 A SW module for CAD-based 3D part recognition system

Description:
The result is an enhancement of a pre-existing SW tool for multi-part recognition and localisation of parts in 3D sensor data, by means of improved robustness. The system is able to recognize and localize and count
- parts with CAD information available or reconstructed,
- parts in arbitrary positions
- multiple parts of same or different type at same time
- with or without a-priori information about their type

Recognition can be extended to new parts automatically by simply adding their CAD description to the database.

Market applications:
The SW system and predecessors have been long-term tested in production lines already and a first version of the new SW system will be ready to market in autumn 2007. A full featured version in 2008.

Stage of development:
The algorithms have been tested and parts of the developed modules have been adapted and integrated for customer projects.

Collaboration sought:
Licensing agreement

Collaborator details:
Companies in the field of robotics, sensors and system integrators are interested in adapting the developed small lot size technology for their purpose.

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2.7 An human-machine AR-based user-interface to painting systems

Description:
An AR (augmented reality) Human-Machine Interface for interactive programming of robots executing paint strokes. The system includes:

- A dummy-paint-gun to be moved by the paint experts "as if he/she would paint the part", extended with markers that are easy to track.
- A camera that tracks the markers of the tool and reconstructs its 3D motions (while being handled by the operator).

Market applications:
The system is a new development already in test-use and will be ready to market in summer 07.

Stage of development:
The algorithms have been tested and parts of the developed modules have been adapted and integrated for customer projects.

Collaboration sought:
Licensing agreement

Collaborator details:
Companies in the field of robotics, sensors and system integrators are interested in adapting the developed small lot size technology for their purpose.

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