Project no. 011838

SMErobot™

The European Robot Initiative for Strengthening the Competitiveness of SMEs in Manufacturing

Integrated Project

Nanotechnologies, Materials and New Processes

Final Publishable Activity Report

Period covered:	March 1, 2005 to May 31, 2009
Start date of project:	March 1, 2005
Duration:	51 months
Coordinator organization name:	Fraunhofer-Gesellschaft Institut für Produktionstechnik und Automatisierung (IPA)
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Publishable final executive summary

Summary description of project objectives

The European Robot Initiative for Strengthening the Competitiveness of SMEs in Manufacturing (acronym *SMErobot*™) was an Integrated Project within the 6th Framework Programme (grant no. 011838) which focused on research, development and innovation related activities towards creating a family of cost-effective versatile and easy-to-use robots. The *SMErobot* consortium has set itself three ambitious innovation goals:

- The new robot should be able to understand, “intuitive” commands, so that it can be shown what to do.
- It should satisfy all safety requirements, so that it can share a workplace with humans.
- And it should be capable of being quickly integrated into an existing manufacturing environment: simply plug and produce.

Demonstrations of fully functional prototypes were set up in real small and medium sized (SME) production environments of different manufacturing branches (wood processing, small-batch foundry, forging industry and metal parts fabrication), with support from SME-type end-users and system integrators. Training and education was conducted at all levels, from researcher to possible end-users. The unique composition of the consortium aimed for maximum European impact on worldwide standards.

The project started in March 2005 and ended in May 2009 after a project run time of 51 months.

Contractors involved

For the first time, the five major European robot manufacturers had joined forces in *SMErobot*™, in close cooperation with key component manufacturers, leading research institutes, universities and consultants for multidisciplinary RTD, dissemination and training efforts. The *SMErobot*™ partners were:

- Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. represented by it’s Institutes: IPA (as *SMErobot* Coordinator), ISI, ISIT
- ABB Automation Technologies Robotics
- COMAU S.p.A.
- KUKA Roboter GmbH
- Reis GmbH & Co. KG Maschinenfabrik
- Güdel AG
- Castings Technology International LTD by Gurantee
- Visual Components Oy

- Rinas ApS
- Prospektiv Gesellschaft für betriebliche Zukunftsgestaltungen mbH (GfAH)
- German Aerospace Center (DLR) - Institute of Robotics and Mechatronics
- Istituto di Tecnologie Industriali e Automazione (ITIA-CNR)
- Lund University / Institute of Technology
- University of Coimbra / ADDF
- GPS Gesellschaft für Produktionssysteme GmbH
- Pro Support B.V.

Additionally the SMEEIG EESV, a so-called European Economic Interest Group (EEIG), was founded to facilitate the integration and cooperation of both SME end-user and system integrator groups with the Consortium. Pro Support managed the EEIG. Its scope of activities covered specification, testing and validation of robot concepts.

Co-ordinator contact details

Fraunhofer IPA acted as project lead. A project office for the day-to-day project management was maintained by GPS Gesellschaft für Produktionssysteme GmbH.

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Work performed

The work performed in *SMErobot*™ was marked by challanging research and development goals, intense partner interactions, remarkable public interest, comprehensive outreach through numerous publications both in the scientific and technical press. Among the highlights were:

- The publicly held two-day *Final Project Workshop* was successfully help on May 07-08, 2009 with presentations and demonstrations of the *SMErobot* results http://www.*SMErobot*.org/15_final_workshop/. Attendants (close to 100 guests) from supply industries, end-users (mostly from SMEs) and research could get hands-on experiences of *SMErobot* results.

- A series of demonstrator Workshops in early 2009 were held at end-user sites to have participants from other SMEs experience the novel *SMErobot* workcells in real productsions. http://www.*SMErobot*.org/05_SME_involvements/.

- A joint booth of close to 250qm at AUTOMATICA 2008, the leading robotics trade fair, was carried out http://www.*SMErobot*.org/14_automatica/. The *SMErobot* booth was regarded a major highlight of the trade fair with remarkable media coverage.

- A final project video was produced to document results, demonstrations and future use of the project's results. http://www.*SMErobot*.org/15_final_workshop/#final_film. Demonstrator-specific video films showcased results, applications and future use of robotic technologies in specific applications and branches.

- The first project video, called "Coffee Break explains the project's aim and approach in an entertaining way has been received with great success in education and industry. http://www.*SMErobot*.org/download/#video.

An abundance of results in the technical workpackage was elaborated by the partners, examples being:

- An all-new robotics system based on parallel kinematics, simultaneously combining the advantages of high stiffness, low cost and modularity

- Modern plug-and-play technologies to replace complex cables and wires

- Safety systems and solutions for safe human-robot interaction

- Easy, automatic program definition with or without CAD data using speech, 3D graphics or programming by demonstration

- New high-density servo-actuator, professional ball joints as well as variable-stiffness joints

- 3D modeller scanning and modelling objects in 3D real-time

- New MEMS-technology-based force/torque sensor for affordable force measurements and low-cost mass production

- Flexible grasp technique and robots using conventional manual tools
- A computerized life cycle costing tool for costing and profitability assessments
- A *SMErobot*™ toolbox with self-explanatory training modules and checklists that support the development and implementation of the new generation of robots.

For all four demonstrations, partners in *SMErobot*™ worked out a common specification scheme including technical, economical and ergonomical requirements. In a further step, the integration, set-up and evaluation for their evaluation process in SME environments was specified. Demonstration partners at both end-users and system-integrators levels were selected and invited into project. The realisations of the four demonstrations (D1 to D4) proved the value of the novel robotics concepts in real small and medium-sized manufacturing environments:

- *D1: Intuitive instruction of fettling of castings for the foundry*. The demonstrator installed at Castings Technologies in Sheffield was based on a completely new robot concept that makes high-performance robotics affordable. The patented innovation behind the new parallel kinematic structure is the asymmetrical clustering of the links in the arm. This design provides a large accessible workspace and lightweight arm system together with high stiffness and accuracy. In the fettling application, the robot was designed for heavy-duty, low-speed process, but it can equally be adjusted to perform high-speed applications such as laser cutting, water-jet cutting, gluing and material handling. The new parallel kinematic structure provides a large accessible workspace and lightweight arm system together with high stiffness and accuracy.

- *D2: Fast installation and small batch size production change*. The robot work cell at Hirschvogel Umformtechnik performs a very common task at SMEs: chaotically stored workpieces in bins need to be gripped and placed in a machine tool. Based on a point cloud of the bin, captured by a 3D laser scanner, the position and orientation of several objects and gripping points are calculated. In order to select the best workpiece for picking, all the possibilities are checked with regard to potential collisions with other objects or with the bin. Modular control architecture also allows fast adaptation of the robot cell to new tasks. New devices, such as grippers, can be easily integrated by combining and parameterizing predefined operations.

- *D3: The SME welding robot*. New teaching methods, sensor integration and a graphical user interface are the main building blocks of the "Intuitive Programming" robot cell at Treffler Maschinenbau. Using force-torque control, the robot is guided manually along the desired path. The worker specifies the relevant points with regard to weld position and collision-free movement. Intelligent algorithms generate the robot program automatically. Another example of programming by manual guidance is the “worker’s third hand” application. In-built sensitivity allows the worker to guide the robot safely and accurately through the workspace. Its sensitivity makes the robot actively compliant, which allows the execution of difficult automated assembly tasks and makes it possible to recognise unwanted collisions. Easy-to-use interfaces enable the robot controller to memorise precisely a sequence of actions, including start and finish positions, robot movements and tool commands.
- *D4: Automation of manual woodworking processes*. The woodworking assistant at Schreinerei Som has been designed to carry out a variety of woodworking tasks at this small joinery business. With its tool adaptor for holding a range of different manual tools, the robot

is able with great flexibility to carry out a variety of tasks, such as milling, drilling and spraying. Operation and programming of the robot is by means of an intuitive man-machine interface, which includes graphics- and speech-based input as well as intuitive robot guidance using a 6D mouse. The robot can also be moved to different workplaces by forklift on its flexible base plate.

The benefits of a *SMErobot* system for its end-user depend crucially on how the system is integrated into the end user's business. That is why *SMErobot* also addresses socio-economic aspects with a range of supportive decision-making and training tools. For SME end-users, developers and system integrators as well as for students and trainees the *SMErobot* Toolbox was designed. It contains a broad array of web-based interactive training and education modules, instructions and checklists for creating a wide knowledge base on the implementation, use, and development and implementation of *SMErobot* systems.

The *SMErobot* Toolbox also provides end-users with a training module – Human-Centered Automation Assessment – with which they can assess their implementation strategy for a robot system. *SMErobot* also offers a range of tailored business and financing models within an intuitive, yet powerful life-cycle costing tool for evaluating the economic benefits of a new robot system. The software delivers a reliable comparison of the costs and benefits of different financing models or between using a robot and working manually.

The project aimed to access the create awareness in the potentials of robot automation by reaching out to end-user industries through "SME-campaigns" to get pioneering companies involved to contribute to specifications and early trials of demonstrators and prototypes.

Through a newly formed European Economic Interest Group (the SMEEIG), companies (suppliers and end-user) could flexibly join the project activities. All industry partners involved in the project's workcell demonstrations entered the SMEEIG. Furthermore, some 40 industries have expressed their interest and support in the project by entering a SME pool.

The Consortium's size required effective leadership and communication:

- The project infrastructure (web site, mailing system, computer supported cooperative work platforms such as BSCW and the internal website) proved highly effective for the day-to-day work.
- Continous media work and public relation contributed to the project's high visibility and effective dissemination to suppliers and end-user industries.
- A quality control scheme has been established for each workpackage allowing quick assessment of the project's overall standing.

End results / Project objectives / Achievements / Methodologies and approaches

SMErobot's mission has been to develop the technologies and components for a wide spectrum of advanced yet low-cost and easy-to-use robotic automation systems. Being productive calls for a combination of flexibility and cost-effectiveness. Therefore, the *SMErobot* consortium has set itself three ambitious innovation goals, which were formulated in three “Thrusts”:

- The Robot Capable of Understanding Human-Like Instructions
- The Safe Human-aware Space-Sharing Robot
- The Three-Day-Deployable Integrated Robot System

The innovations were grouped into six research and technology-oriented workpackages (R1 to R6). Results were integrated into the four demonstrator scenarios in different applications (D1 to D4). Further innovation related topics addressed the project’s educational and training goals (workpackage TE), socio-economic challenges (ISE and IEX), and standaridization issues (Workpackage STD).

WP R1 “Shop-floor suitable devices for intuitive robot interaction”: In the first project year, a detailed state-of-the-art analysis of existing interaction devices was performed. The analysed devices were rated taking typical tasks and processes as well as use cases of SMEs into account. In the second year, R1 was mainly dominated by implementation work for new human-robot interaction devices improving the approaches from the first period. This made many different devices available, e.g. new devices for jogging and operating the robot as well as several basic technologies for building innovative interaction devices have been realized, e.g. Force-Torque-Sensors, wireless communication, a safety module and basic algorithms for speech and gesture recognition.

During the third and fourth project year, the focus in the Work package R1 was on the realization and optimization of the input devices: New handle for lead through and speech interface in D1, *Safe Game Pad* in D2, *Teach Wand* in D3 and *Flybook* in D4. This work was mainly performed locally (single partner/bilateral). Besides the work on the devices, KUKA and Reis detailed the specification of the vendor-neutral device interface and implemented first commands on their controllers. These devices have been also integrated into the demonstrator or demonstrator-near test beds. One focus in the last few months has been the evaluation of the devices. User acceptance was tested by performing user tests in several workshops. The following devices were developed: New handle for lead through and speech interface in D1 and D3, Safe Game Pad in D2, Teach Wand in D3 and Flybook in D4.

WP R2 “Intuitive task and motion definition”: In the first year, partners worked both on the theoretical background (state of the art, interface concepts), and on first implementations in test beds of the addressed programming means – speech and gesture, manual guidance, production data and high-level programming. In the second year, results and experiences regarding speech interaction, programming by demonstration and CAD like programming, focused on the use in the later demonstrations of *SMErobot*, were created. In the third year, work mainly delt with the integration of the components into the demonstrator and AUTOMATICA exhibits.

In the last year, the results of the R2 work package were demonstrated at AUTOMATICA in Munich, the different demonstrator workshops and the final event in Stuttgart: programming methods based on demonstration, sketches, speech and application sheets enabled the *SMErobot* exhibits to be programmed in an intuitive way as suitable for SMEs. The highlights of the spectrum of results consisted in the ABB *Lead-Through Server*, the COMAU and ITIA manual guidance device, the *Smart User Interface* for welding applications realized by KUKA, the Reis Application sheet and sketch editor, the Rinas interface to offline programming, the DLR interface to the *3D-Modeller*, the *Service Oriented Architectures* (SOA) by ADDF, the ontology-based man machine interfaces by LTH and the intuitive *programming by demonstration* robot cell by IPA.

WP R3 "Physically harmless and low-cost kinematics": In the first year, suitable kinematic models were developed for a new-patented parallel kinematic robot with large work space in relation to its foot print. These models were implemented in virtual robot prototypes and as a physical pre-prototype to control in both joint- and Cartesian coordinates. In the second year, experiments and simulations were performed with collisions between robots and dummies. The light-weight drive units for the wrist in the D1 robot have been assembled and tests were running with promising results on torque to weight ratio. The design of the D1 robot became ready and new components were tested on a first prototype. In the third year, the virtual prototyping of the D1 robot and the design of the robot and the design of the arm system of the D1 robot and the arm system were finalized. A servo actuator for the use in the modular wrist of the D1 robot was designed and manufactured.

In the fourth year, finite element crash simulations have been adapted for the experimental setup, verification and calibration for future computations. The partners analysed the worker's third hand application presented at AUTOMATICA with respect to safety aspects. Further development was made to increase the performance of the brake and the capacitive encoder of the Servo actuator used in the wrist of the D1 PKM (Parallel Kinematic Machine) robot. In total seven servo actuators were manufactured. The development of the joints for the PKM robots has continued and a new set of joints was designed and manufactured for the desktop PKM used for testing of new actuation- and control concepts. A new high stiffness guide way system was developed. It consists of roller blocks and rails. The *F1 PKM* was developed using the same type of linear guide ways as for D1. While the D1 has been equipped with a serial wrist in order to increase the number of degrees of freedom (DOF), a parallel wrist concept was developed for F1. The *Tabletop Tau* PKM robot was enhanced. Dual motor actuation, new linear guide ways, new joints, new carbon wrist platform and new framework were worked out and integrated. The D1 robots have needed substantial work including software development, system configuration, servo loop tuning, force control tuning, lead through server installation, safety equipment installation, robot programming and training of operators. Demonstrator assessments were made with very good results. LTH developed calibration software for the D1 robot. The force control for lead through of Demonstrator 1 was further developed, comprising a 6 DOF force/torque sensor, tool identification functionality, a new safety handle and an I/O interface for process tools. A new concept expeimentally validated for the elastic element unit in the variable stiffness joints. Further development of the *MEMS 6 DOF Force/Torque Sensor* was optimization of the deep reactive ion etching process, fabrication of wafers, design and manufacturing of new sensor electronics and development of new software.

WP R4 "The safe & productive robot working without fences": During the first year, major results concern the definition of a new safety concept named Collision Avoidance Object and the specification of functional and technical requirements of safety sensors focusing on, respectively, capacitive sensors, 3D-Time-of-flight visual sensors, 3D-multisensory device (3D Modeller) and F/T sensor. In the second year, the prototype of the 3D-Modeller regarding the development of safety sensors had been completed. Furthermore, proximity sensors and human and robot detection and tracking algorithms were improved. With reference to collision avoidance, a template for the logic control of the robotic workcell and investigated in simulation strategies based on artificial potential fields was proposed.

The third year's activities were addressed especially in the improvement and assessment of the sensing systems and collision avoidance strategies developed so far. Several test beds were realized for this purpose. New algorithms for automatically obtaining models with shape variation for unordered point sets, and for tracking of multiple humans by using multiple images coming from standard surveillance cameras were developed. Many experiments have been performed using a test-bed made by the actual robot, a moving virtual operator (i.e. a dummy) considering both static and moving obstacle.

In the last year, "Integration of sensing and robot control and set up for test beds for safe human-robot space sharing" were finalized. In this task three different topic were addressed: first, the integration of "safe sensors" in the supervision of the cell in order to have safe robot working without fences; second, the definition of control strategies of the robot in order to achieve a safe behavior of the robot with respect to human operator and/or moveable obstacles; and third, the integration of sensors and algorithm into test beds. In the last year of activities, efforts were spent both in the further investigation of the theoretical aspect and in the in the definition and exhibition of the results achieved at the AUTOMATICA fair in Munich. The algorithms, the surveillance system and the robot were integrated in the version developed for AUTOMATICA of the Demonstrator D2. The collision avoidance algorithms were modified to allow an easier implementation in industrial set-up.

WP R5 "Mechanisms and architecture for 'plug-and-produce": In the first year, The SME end-user requirements were collected and the survey of available technologies prepared. Different industrial communication technologies and protocols were investigated. An evaluation scheme for finding the "best" real-time communication bus was specified. In the second year, the plug & produce concept has to be considered and extended to the production phase, so that we could claim that the systems are semiautomatic when they are deployed and operated. For input device (PDA, WebPad, PC) has been defined a protocol named External Device Protocol.
In the third year, efforts were sepnt on the evaluation and improvements of XIRP-based *Plug and Play* (PnP). On lower level of communication, academic and research partners have assembled an EtherCAT PCI-board which will be used for the deterministic, real-time PnP-able slave interconnection i.e. sensors, drives, controllers. Several implementations of the mechanical interfaces between manual tools and the robot flange were completed. On the same topic, the RFID for informing the *Light Weight Robot* about the physical properties of commercial tools was introduced.

In the last year, all the partners have positively contributed to reinforce and complete the PnP-scenario. First results were showcased during the AUTOMATICA 2008 fair, where the cell controller, sensors and actuators had been integrated integrated. The cell controller was a PC communicating on an Ethernet network where different protocols were implemented. The device connected had a server or a client for implementing the Plug and Produce. A user-oriented interface was available for programming the process sequences in the cell. On October 2008, the demonstrator D2 linked to R5 has been duplicated at the end user site for proceeding with development in our laboratories and having a real test bench in a production environment.

WP R6 "Robot task generation based on product/process data": During the first year, calibration of models was crucial and has been a focus area. Both a survey of existing means and development of new devices and methods were achieved. Two test beds were specified to illustrate the different research topics, giving a context for innovations and a way to communicate to SMEs. In the second year, integrated *use cases* which show the present work including prove of concepts were in progress relating to automatic task programming, calibration and sensors. Generation of task programs use software for processes arc welding and grinding, a demonstrator focuses on sensors, calibration and world model reconstruction. In the third year, the work moved the focus from fundamental issues to the integration into test beds and proof of concept.

In the last year, the main objective was been to integrate the Rinas task level programming in demonstration site solutions. The first was demonstrated at the *SMErobot workshop* at KUKA in March and the latter was demonstrated at the final *SMErobot* event at IPA in May. Both presentations had a very positive response from guests. As planned, the demonstrations showed a seamless workflow including SOA based automatic orchestration of services, integration of partner contributions, as well as automatic task-level programming of collision free robot programs with integrated fine calibration and welding process. The controlled components included a laser distance scanner and a 2-axis manipulator. Results based on sensor-based registration and related support for task generation and programming was concluded. The 3D-Modeller functionality was verified with test on the lightweight arm for scanning of objects and reconstruction of CAD models of objects. The 3D-Modeller was also integrated to the robot for task programming support demonstrated in D4.

WP D1 "Intuitive instruction of fettling castings for the foundry": The objective during the first year was to establish the requirements from a user point of view related to the use of robotized fettling including a PKM robot structure and also the new technologies that will be developed to make integration and use of the robot much easier and intuitive. In the second year, the specification of the demonstrator was defined and project started the focused research for the targeted application. There is a good understanding for the needs and requirements from the foundry business and the transformation from the user needs was done in order to create a platform for the new technologies to be tested. In the third year, the final design of the D1 robot and cell was ready and the robot, the wrist drive modules and the grinding tool were manufactured. Several components and several partners were involved in the manufacturing, the assembly, the system integration and the software development.

In the final year, the D1 PKM and IRB4400 robots were installed in the foundry area at CTI, Sheffield to form a burning and slitting/grinding cell. This work included software development, system debugging, actuator configuration, system configuration, servo loop tuning, force control tuning, lead through server installation, safety equipment installation, robot programming, training of operators, and extensive tests of cutting, slitting, and grinding operations using lead through programming. The processing operations were carried out on carbon steel and titanium castings using the developed end effectors to process castings. The automated oxy-fuel cutting process achieved by the robot gave 80% reduction in material removal and completely removal of an additional operation from the production cycle. For the slitting operations a head removal time of 7 minutes was obtained, compared 15 minutes for a manual slitting with the same quality. All involved in the tests of Demonstrator 1 were confident that the presented automation concept is the fettling solution that the casting industry has been waiting for. A cost effective analysis was made which showed that it was possible to obtain a pay-off time of less than two years for the demonstrator concept. Due to the rapid upcoming economical crisis starting during 2008, neither ABB nor Güdel could precede the development towards products. Some of the development will instead proceed in a Swedish project with government support (project ProFlexa sponsored by the Swedish Foundation for Strategic Research) and the PKM robot concept will be studied for aerospace applications by Boeing and the University of Deakin in Australia. In addition, Hexagon/Leica, Siemens and MAG have started investigations of the new PKM robot concept.

WP D2 "Fast installation and small batch size production change": In the first year, the appropriate demonstrator scenario had been completed: a small company that produces small metal parts that requests to be able to switch to new families of products or between different batches. In the second year, the activities had been concentrated on the improvement of the current specification of *SMErobot* Demonstration D2 (Plug and Produce / bin picking / machine tending) and the evaluation of a possible alternatives in other sector, such as a small mechanical workshop of a goldsmith or the food industry. In the third year, the activities were mainly focused on WP R5 and in the linked demonstrator WP D2. A good result was the convergence between partners for adopting the XIRP protocol. Two test-beds were included in this demonstrator D2: a SMART NJ1 robot for developing the Collision Avoidance test-bed of WP R4 and the SMART NH3 robot for the bin-picking and XIRP communication for the test-beds of WP R5.

The major activity during the fourth year has been the preparation of Demonstrator D2 in two versions. A first version, which presented new safety concepts, was installed at the *SMErobot* booth for AUTOMATICA 2008 on June 2008 and a second version, more oriented to a real shop floor was installed at the end user site of Hirschvogel in Denklingen (Germany) on October 2008. These two versions run in parallel in Stuttgart at the Fraunhofer IPA facilities and at the end user site for constantly improve performance without disturbing the customer production. In this cell has been integrated the RTD contributions from WP R5 about the Robotics Plug-and-Produce, from WP R4 for the Collision Avoidance strategy and from WP R1-R2 for the intuitive programming devices and the programming by demonstration.

WP D3 "Robot assistants as multi-purpose tools": In the first year, detailed analyses of several SMEs were performed to select and specify one or more appropriate demonstration scenarios for Thrust 1. It had been decided that setting up multiple demonstrators would be most beneficial for the involved SMEs. Each demonstrator was motivated by a specific SME use case and integrates a subset of all developed functionalities within *SMErobot*, thus leading the way towards truly useful robot assistants for SMEs. The second year was dominated by discussions between KUKA and their prospective system integrators and end-users. Two system integrators (ZS Automation and KINE) and two end-users (Treffler and K.MET) were finally selected. First hands-on experiments were gathered with traditional programming methods and helped the partners to incrementally improve the robot system to eventually become a flexible robotic welding assistant. The third year was dominated by refining and implementing the detailed specifications of the D3 demonstrators that were originally developed in the previous year. Two end-users (Treffler and K.MET) and three system integrators (ZS Automation, KINE and MRK, a third party of KUKA) as well as the research partners have been working hard to integrate the project's RTD results into test-beds and demonstrators.

In the fourth year, two robot cells, "The SME Worker's Third Hand" and "5 Minute Robot Programming", have been pushed for showcasing them at AUTOMATICA 2008. At the beginning of the fourth project year, the initial robot cell set up at the Treffler site was still used as a vehicle to obtain requirements and test cases from hands-on experiments based on traditional programming methods. Later, several evaluation sessions at Treffler, KUKA and IPA took place to rate the technologies to be integrated into the final demonstrators. Similarly, K.MET was feeding the D3 integration work at KINE with their requirements. Due to resource problems, KINE could only set-up a demonstrator based on image-based programming of welding steel grids towards the end of the project. All demonstrators and test-beds were eventually evaluated during workshops at KUKA, Treffler and KINE which where attended by several companies interested in robot welding. The final exhibition of the two main D3 demonstrators took place at the project assessment and final presentation workshop. The feedback to the live demonstrations and the two presentations of D3 material and videos was overwhelmingly positive.

WP D4 "Robot assistant for a woodworking facility": In the first year, the main work comprised the definition of the scenario in the application area woodworking. To achieve this, different partners visited several companies working in the area of woodworking.
In the second year, the detailed demonstrator specification was one of the major. An "Information Day" for SME companies at the German association for companies from the wood and plastics sector ("Fachverband Holz und Kunststoff Hessen") was held on January 26, 2007.
The major topic during the third year was the integration of devices and modules into demonstrator D4. One major integration topic was the integration of the DLR 3D Modeller into the Reis robot control and demonstrator D4. Furthermore, planning activities to prepare the exhibits for the booth at the AUTOMATICA 2008 Fair in Munich in June were continued during the reporting period.

In the fourth year, major activities were related to prepare the exhibit and to present the exhibit on the common booth at the AUTOMATICA in June 2008. Reis participated with an exhibit related to demonstrator D4 called "Woodworking Assistant" that was used to demonstrate a subset of demonstrator D4 functionalities. Major activities during the final project phase were the finalisation of the Application Sheets and the Sketch Editor and their integration into demonstrator D4 as well as evaluation and optimisation the user interfaces together with end users. Two D4 workshops to present end evaluate the realised research work related to demonstrator D4 were held together with potential end-users in January 2009. During the Final Workshop, demonstrator D4 was presented by a speech and a practical demonstration.

WP TE "Training and Education": In the first year, the training activities aimed mainly at supporting the processes of technology development, implementation and testing of prototypes. First pilot trainings to support the manufacturers and researchers in identifying use-cases were developed and conducted. The second pilot trainings were "technology analysis and evaluation through user participation". In the second year, activities focused mainly on the co-operation with a vocational school and on pushing the SME Campaign. Both activities aim at disseminating *SMErobot* knowledge among future "customers" that will stimulate a demand on SME suitable robots. In the third year, activities concentrated mainly on the co-operation with the project partners, accomplishment of workshops, interviews with developers, system integrators and SME end-users as well as the diffusion of Training & Education related topics within the project and the scientific community nation- and Europe-wide. Regarding to the

AUTOMATICA 2008 Prospektiv's actions focused on the development of the *SMErobot*-toolbox.

In the fourth year, one focus of activities was the preparation and implementation of the AUTOMATICA booth exhibits. In this context particular relevance had the further completion of Prospektiv's *SMErobot*™ -Toolbox and the programming of the tabletop PKM for teaching purposes by LTH. Another major achievement in this reporting period has been particularly the evaluation of the *SMErobot* demonstrators. An appropriate concept to evaluate the usability and user-friendliness of the demonstrators was developed and implemented in several workshops with SME end-user groups. Furthermore – among other various transfer activities – over 100 German vocational schools were contacted to present the developed *SMErobot*™ -Toolbox.

WP IDS "Dissemination": One of the highlights of the first two reporting years was the completion of the *SMErobot*™ video. The consortium produced and distributed two thousand DVDs to carry the *SMErobot* message into the world. In the third year, decision was made to present important project results on a joint booth at the ATUTOMATICA 2008 trade fair in Munich on June 10 to 13. While preparing the AUTOMATICA 2008 event substantial press material has been completed and distributed. In addition, a *SMErobot* fair flyer was designed. To support the overall PR activities of all project partners a digital press package with a various number of videos, texts and images was completed.

The last year, multiple dissemination activities had large impact: The project presentation on AUTOMATICA, Europe's leading robotics trade fair, in June 2008, and its 13 exhibits met with very positive resonance from press and visitors. A series of workshops for each Demonstrator at end-user sites in early 2009 gave important feedback on end-user level. Ultimately, the Final workshop represented all final results on May 7-8, 2009, in Stuttgart. In addition to the Project Video "Coffee break", a Final Project Video showed the demonstrators in real environment.Due to intensive PR work, online traffic on www.*SMErobot*.org was extremely high during the three months before and after AUTOMATICA as well as for the last project months (e.g. during the time of the Demonstrator Workshops and the Final Workshop).

WP IPR "Intellectual property rights": Partners filed intellectual property rights mostly in the first two years of the *SMErobot*™ project, the service of the work package IPR has been set up and adjusted. One example for this service is the settlement of IPR matters in combination with the MEMS-force torque sensor with satisfaction of all partners. ProSupport, GPS and IPA provide mediation in the case of IPR problems. Both action lines have been active in the whole project period.

WP ISE "Socio-economics": In the first year, interviews in Italian SMEs were conducted in order to assess SME's requirements regarding flexible and save robotic solutions as well as their demand for new business models. Moreover, technical, economic and social impact indicators were developed and new indicators for estimating the socio-economic impact of *SMErobot* were added. In the second year, one of the major achievements was the conduction of 17 interviews with SMEs in different European countries. Based on further interviews with robot manufacturers and system integrators new business models were designed and evaluated. In addition, data of the German Manufacturing Survey 2003 was analyzed concerning the current use and unused potentials of robots in German manufacturing companies. First estimations on how the new technology being developed in the frame of *SMErobot* is supposed to influence social, technical and economic indicators have been developed. In the third year, seven interview sessions with robot manufacturers and system integrators were conducted in Germany, Italy, Sweden and Switzerland. The goal of these interviews was to capture robot manufacturers' and system integrators' range of industrial services offered as well as the experiences made with these offerings. Moreover, in case that services which were identified as important in the interviews with SMEs were not provided, possible reasons for the lack of these services were investigated.

In the fourth year, the partner realized three major achievements. First, the results of the interviews about new business models conducted with robot manufacturers/system integrators and SMEs are presented in deliverable D ISE 3 containing the development and evaluation of new business models for robot industry. The second achievement during this period was the realization of 482 telephone interviews in six selected European countries about the potential of the robot technologies developed in the frame of *SMErobot*. There seems to be a large potential for the developed technologies. Third, the socio-economic impacts of the implementation of a robot for SMEs have been assessed at all four demonstrator firms, with nearly consistently positive results.

WP IEX "Exploitation": In the first two years, a draft version of an excel-based tool to calculate life cycle costs (LCC) of SME suitable robots was developed. The LCC-tool not only supports SMEs in their investment decision whether or not to purchase a robot but also serves robot manufacturers and system integrators in pointing out advantages of implementing a *SMErobot* system. Furthermore, a questionnaire for conducting interviews with robot manufacturers and system integrators on innovative business models were developed.
In the third year, the life-cycle costing tool was subject to major refinements and extensions. Based on feedback gathered in internal workshops, the tool was upgraded. Additionally, a workshop concept for a multiplier workshop was developed. The workshop aims at presenting technical and non-technical project results to transfer institutions.

In the last year, the life-cycle costing tool was subject to more refinements. Based on feedback of system integrators, the tool was upgraded. A tool for assessing the developed business concepts has been developed. It has been exemplarily tested for the business model "ramp-up assistance" where the perspectives of both the customer and the provider are considered.

WP IST "Standardization": In the first, a first survey of ongoing standardization activities in the robotic area was presented and discussed with all IST partners during the first project year. All ongoing partner activities concerning standardization are monitored, reported, summarized and discussed by the involved *SMErobot* partners.

The following actions were pursued throughout the complete project runtime and completed during the final year: 1.) Participation of the robot manufacturers in ongoing standardisation activities concerning *SMErobot* issues and 2.) Checking *SMErobot* activities concerning standardisation possibilities and introducing them to adequate standardisation bodies.

WP MA "Management": The project management administrated financial, contractual, IPR and other legal matters, steered the reporting, and monitored and updated work plans through out the project. Partner GPS operated the project office, scheduled meetings, moderated and made local arrangements as well as implemented a monthly (virtual) board meeting of the Management Board. The project office provided communication services like preparation of agenda and handouts, taking minutes, or provision and maintenance of communication infrastructure, as well as implementation of processes for communication and collaboration in virtual meetings. Establish quality control schemes from beginning on partners have made valuable experiences with, e.g., traffic light reports, deliverable peer review, open and anonymous feedback loops at workshops, presentations, rehearsals etc. Regular project internal reviews, particularly before annual review (“rehearsal”) for possible re-planning of work, were all part of the quality assurance. The project management stressed proactive measures such as defined partner roles, measurable deliverables, detailed project plans and contingency plans on all levels to ensure highest quality in the project work.

Impact on industry and research sector

SMErobot has become a synonym for a joint European efforts by robot automation industries to give new impetus to the introduction of robot technology in small and medium-sized businesses: An entirely new, modular and interactive generation of robots which, in addition to being quick to install and easy to operate, will also help to make European SMEs more competitive thanks to their cost-effective design. The project has been a resounding and widely recognized success:

- To date robotics technology has been the result of requirements motivated by the automotive industries’ productivity and cost needs. The project has motivated the development for automation equipment for non-automative industries badly in need for strengthening their competitiveness. Through extensive public relation, showcasing results, publications, trade fairs, etc. *SMErobot* has become a synonom for a strong vision and mission towards competitive small and medium sized manufacturing and innovation driven suppliers.

- Pilot trials in small and medium-sized enterprises from the fields of casting, mechanical engineering and metal- and wood-working were used to prove the innovation potential of the technologies and applications. Numerous stakeholder groups took part in the trials with mostly positive feed-back.

- It is undisputed that SMErobot contributed significantly to the innovation lead of robot automation suppliers.

- European industrial robotics research has been revived by this project

The project has established itself as a brandmark and has received highest recognition and reward from robotics research, robot equipment suppliers and particularly end-users of all domains and sizes. The Consortium has very much enjoyed the project in all its facets: research, demonstrations, reach-out and networking. The wide variety of results, both in terms of knowledge, demonstrators, prototypes and software tools have to undergo the typical product life-cycle following the project runtime: from pre-competitive products and services towards innovations for the benefit of a European automation supplyindustry and end-users:

- In the short term, it is estimated that especially software-related components will reach marketability. These products out of SMErobot research will be: robot safety controllers, teaching by demonstration, shop-floor-suitable simulation tools, life-cycle costing tools, SMErobot Toolbox (teaching, training), object detection and identification (bin picking).

- In the midterm, component-oriented results are aimed to reach market maturity levels such as high-performance drives, force-torque-sensors, parallel-kinematic designs, integration of novel interfaces in robot instruction such as voice, pointing, plug&produce networks and optical sensors for active safety monitoring etc.

- Larger systems such as novel kinematic designs for SMEs, variable stiffness robotic arms, will reach maturity levels in the long term

Photos of the project work

For further photos and high-resolution files, please visit the project's Electronic Press Kit: http://www.*SMErobot*.org/press/

Figure 1: New parallel kinematic machine (PKM)

Figure 2: Plug-and-Produce Cell for Bin Picking Applications

Figure 3: The Worker's Thrid Hand

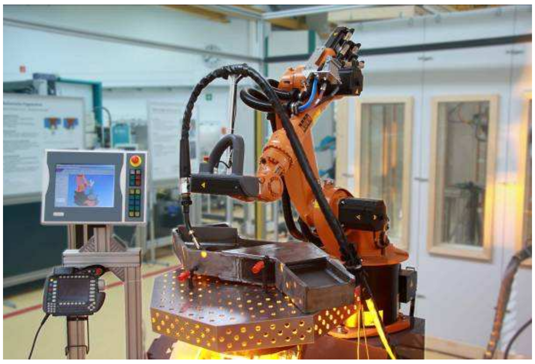

Figure 4: Programming through Manual Guidance and Graphical Post Processing

Figure 5: D4 - The Woodworking Assitant

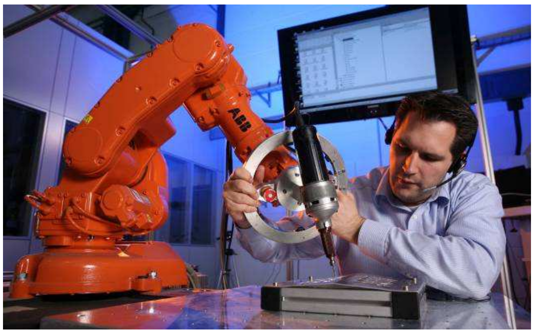

Figure 6: Manual Guidance with Voice Interaction

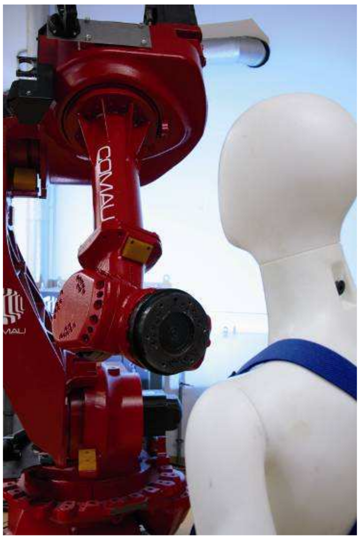

Figure 7: The Safe and Productive Robot Working without Fences

Figure 8: Safe Human-Robot Interaction

Figure 9: SMErobot Toolbox

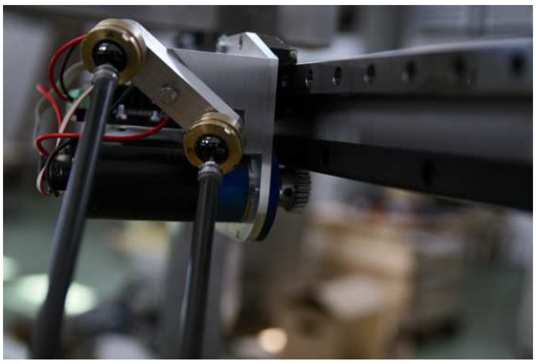

Figure 10: Tabletop PKM / Tau Robot

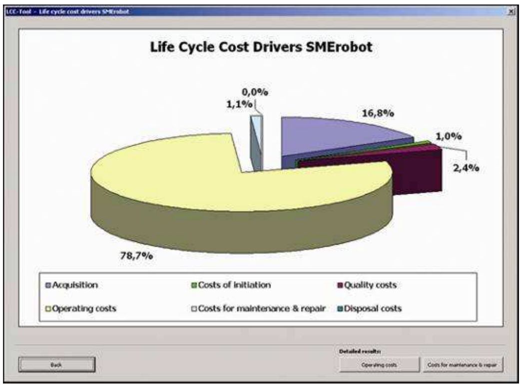

Figure 11: Life Cycle Costing (LCC) Tool

Figure 12: New HDSA High Density Servo Actuato

r

Figure 13: 3D-Modeller

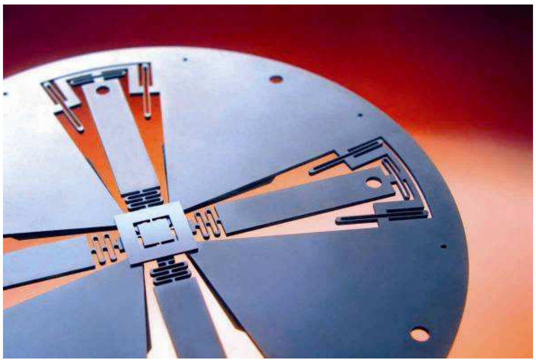

Figure 14: New Low-Cost MEMS-Technology Based Force/Torque Sensor

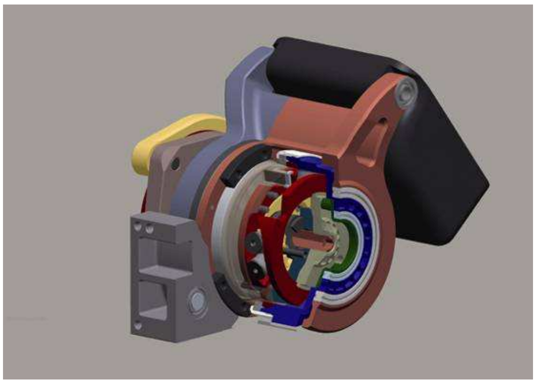

Figure 15: Variable Stiffness Joint

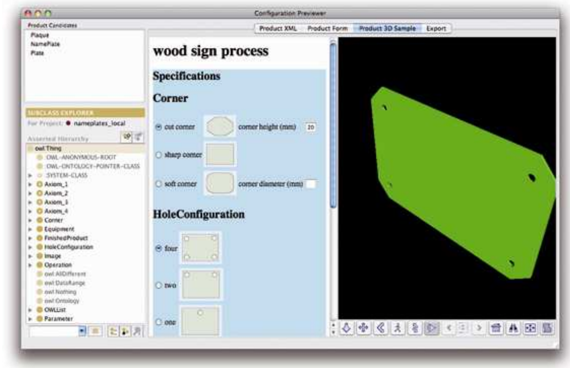

Figure 16: Automatic Generation of User Dialogues

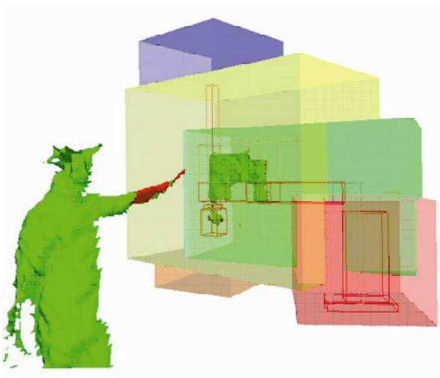

Figure 17: Human-Robot-Cooperation

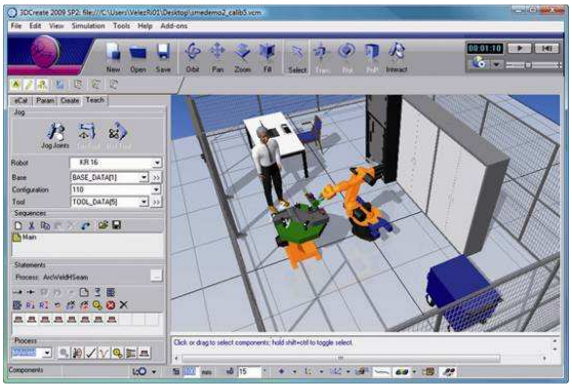

Figure 18: SEMI Automatic Programming with 3-D-CAD

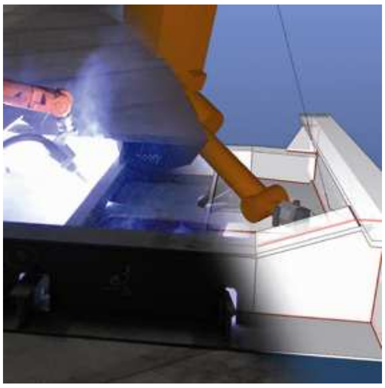
Figure 19: Automatic Robot Programming


Figure 20: Exactaburn Cutlight

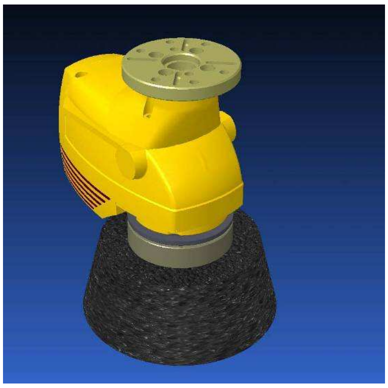
Figure 21: Grinder

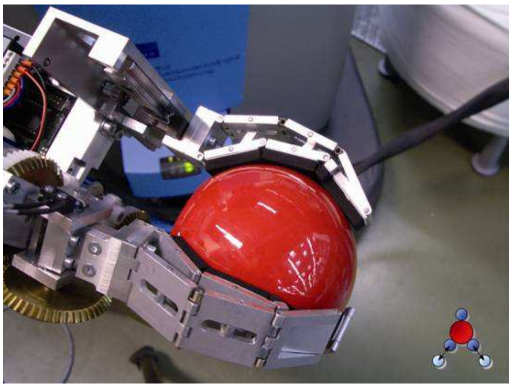
Figure 22: Flexible Grasp Technique

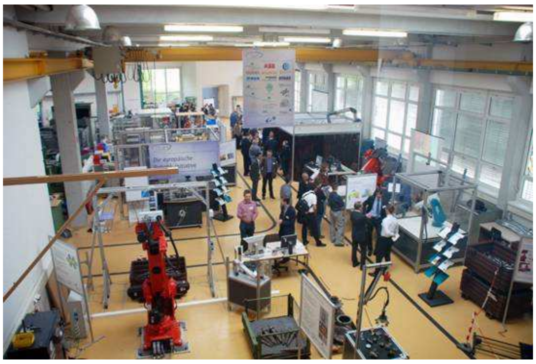
Figure 23: Impression from the Final Workshop (1)

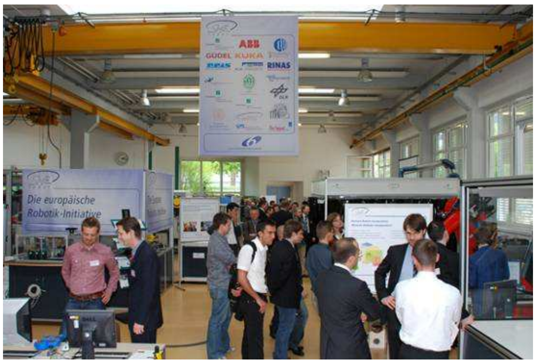

Figure 24: Impression from the Final Workshop (2)


Figure 25: Impression from Automatica 2008 (1)

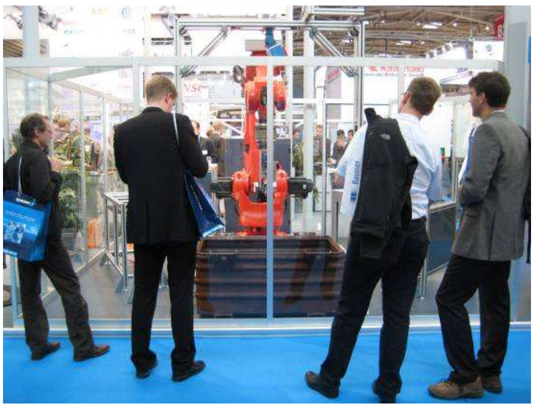
Figure 26: Impression from Automatica 2008 (2)

Figure 27: Impression from Automatica 2008 (3)

Figure 28: D1 the oxy-fuel cutting robot

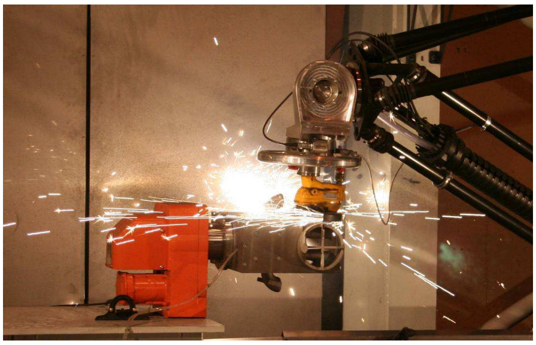

Figure 29:D1 slitting performed on a titanium casting

Figure 30: D2 Plug'n'Produce cell controller

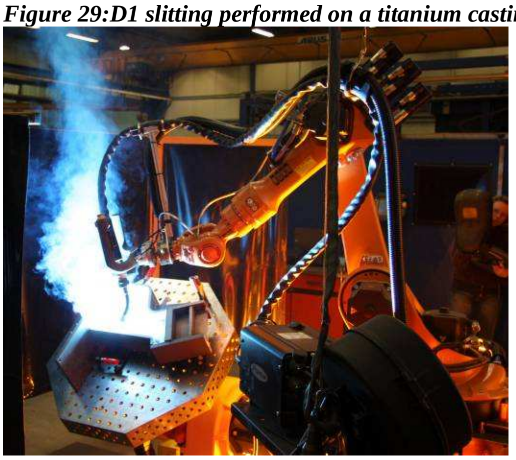

Figure 31: D3 welding tests

Figure 32: Master Joiner Som guiding the D4

Website

For further information about *SMErobot*, please visit:
[www.*SMErobot*.org](http://www.SMErobot.org)

Annex I – Publishable results of Final plan for using and disseminating the knowledge[1]

1. result	
Name	InTeach Programming Environment
Description	An intuitive programming environment for industrial robots. The environment consists of different modules for recording the trajectory, postprocessing and replaying, also for the integration of different modalities and sensors. Up till now the programming environment has been implemented in two applications on Reis and KUKA robots. Speech interaction and input devices like 6-D mice are available as modules.
Possible market applications or use	The programming environment is dedicated to users of robotic systems with small lot sizes, e.g. small and medium enterprises, but also development departments. Application scenarios are in first case trajectory based movements, e.g. arc welding, gluing, etc.
Stage of development	Research prototype, implemented in several robots
Collaboration sought or offered	Development collaboration
Collaborator details	The programming environment has to be developed from research to industrial strength software. A system integrator with different customers in the low lot-size area would be the best partner.
IPRs granted or published	./.
Contact details	Fraunhofer IPA, Christian Meyer. crm@ipa.fhg.de, +49 711 / 970-1092
2. result	
Name	Visual Components' 3DCreate 3.2
Description	A new version of the simulation framework has been developed including the (applicable) development done within the *SMErobot* project
Possible market applications or use	3DCreate is the simulation development toolkit of Visual Components, a leading SME in the area of simulation of manufacturing systems
Stage of development	Beta release, Final release scheduled by May 25th, 2007
Collaboration sought or offered	Guidance from robot manufacturers was sought for improving the simulation framework

[1] ***Knowledge:*** means the results, including information, whether or not they can be protected, arising from the *project* governed by this *contract*, as well as copyrights or rights pertaining to such results following applications for, or the issue of patents, designs, plant varieties, supplementary protection certificates or similar forms of protection (Article II.1.14 of the contract)

Collaborator details	The entire development was done in-house
IPRs granted or published	All copyrights belong to Visual Components.
Contact details	Ricardo Velez, R&D Manager, ricardo.velez@visualcomponents.com
3. result	
Name	Visual Components' 3DCreate 2009
Description	A new version of the simulation framework has been developed including the (applicable) development done within the *SMErobot* project
Possible market applications or use	3DCreate is the simulation development toolkit of Visual Components, a leading SME in the area of simulation of manufacturing systems
Stage of development	Final release September 2nd, 2008
Collaboration sought or offered	Guidance from robot manufacturers was sought for improving the simulation framework
Collaborator details	The entire development was done in-house
IPRs granted or published	All copyrights belong to Visual Components.
Contact details	Ricardo Velez, R&D Manager, ricardo.velez@visualcomponents.com
4. result	
Name	Final report on the user potential of the developed new robotic technologies
Description	Currently available statistics about robots do not differentiate between varying firm sizes. So there exists no information if the existing robot technology meets the needs of small and medium sized enterprises (SMEs). This study provides actual representative data of SMEs in six selected European countries regarding industrial robots. First, the current robot use and (further) investment plans are depicted across countries, sectors and firm size. One third of all companies already uses robots in their production, and 11 percent actually plan to install new robots. Then, information about the reasons for not using robots is provided. In the last chapter the attitude of SMEs towards the technologies developed in *SMErobot* is illustrated. The features which were most interesting for the enterprises were robots with an integrated collision avoidance system and robots which can be programmed easily not only by robot experts but also by workers without specific knowledge. A concluding estimation of the potential use of *SMErobot* technology gives a quite encouraging outlook of the future demand. About 6 500 SMEs will potentially invest in this technology yearly.
Possible market applications or use	Estimation of potential users for robot manufacturers and system integrators

Stage of development	Final
Collaboration sought or offered	Collaboration for estimation
Collaborator details	Robot manufacturers helped to describe the technological developments
IPRs granted or published	./.
Contact details	Fraunhofer ISI, Ute Weißfloch, ute.weissfloch@isi.fraunhofer.de
5. result	
Name	Report on the socio-economic impacts of the new robotics solution
Description	The report depicts the socio-economic impacts of the developments of *SMErobot* at the example of the four demonstrators. Interviews about the social impacts have been conducted with a robot manufacturer or system integrator and the end user and the Life cycle costing (LCC)-Tool – former developed in this project – has been applied. For all cases the results are rather positive.
Possible market applications or use	Estimation of the socio-economic impacts of the developed technologies for end users
Stage of development	Final
Collaboration sought or offered	Collaboration for the development of questionnaire
Collaborator details	Interviews with demonstrator firms and robot manufacturers
IPRs granted or published	./.
Contact details	Fraunhofer ISI, Ute Weißfloch, ute.weissfloch@isi.fraunhofer.de