TrimBot2020 Deliverable D8.11

Project Exploitation Plan

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Abstract:

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The exploitation plan describes how the developed methods, components and systems could be exploited and outlines potential product fields including different business model scenarios. The report first identifies potentially exploitable results, including algorithms, components, subsystems and systems and then describes the exploitation plans of the relevant partners.

Contents

1 Objectives

Robots for domestic use are very limited in their applications today. At the moment, mainly vacuum cleaning robots, wet cleaning robots and robotic lawn mowers are on the market. The ability of vacuum cleaning robots significantly increased in recent years and now some of them are able to map their environment to operate purposefully and efficiently. In the field of lawnmowers, however, little progress has been made with regard to the intelligence of the robots in recent years. Most of them still drive randomly through the garden to mow the lawn. They also require the installation of a perimeter wire to define the working area. The use of mobile robots for gardening is currently limited to mowing the lawn. One of the reasons for this is that localization in and mapping of outdoor gardens is much more challenging then indoor scenes. This also makes the use of mobile robots for other tasks in the garden more difficult. This is exactly where the TrimBot2020 project comes in.

The objectives of the TrimBot2020 project are to provide technologies and solutions to the challenge of gardening robots. The focus is, however, not exclusively on consumers, but is also aimed at professional gardeners for applications in parks or public gardens. The use cases addressed in the project are trimming of boxwood bushes and cutting of roses. However, the developed methods and algorithms e.g. environment reconstruction, scene understanding or localization and navigation are not limited to these use cases and can be exploited by gardening robots in general. The results of TrimBot2020 also enable the development of gardening robots for other use cases and tasks.

This exploitation plan describes how the developed methods, algorithms, systems and sub-systems can be exploited. It is based on initial exploitation plans developed and documented as part of Deliverables D8.4 and D8.7. The report first identifies potentially exploitable items, including algorithms, methods, components, systems and sub-systems. Subsequently, strategies are presented for commercial and scientific exploitation.

2 Exploitation Items

There is a large number of algorithms, technologies and methods that can be exploited individually. There are also systems and sub-systems like the camera system or the trimming tools that can be exploited independently of the overall system of the TrimBot2020. In the following all exploitable results of the TrimBot2020 project are listed by project partner.

2.1 Bosch

- Robot behavioral modeling by FlexBE
- Ground truth data recording techniques
- Mobile robot navigation in gardens
- Visual feedback control methods for mobile platforms

2.2 ETH Zurich

- Synchronized multi-camera system (based on existing technology developed at ETHZ)
- (Semantic) SLAM system

2.3 University of Amsterdam

- Intrinsic image decomposition algorithm
- Semantic segmentation algorithm
- Synthetic garden dataset

2.4 University of Edinburgh

- Scene labeling tool
- Ground truth datasets
- Point-cloud alignment algorithm

2.5 University of Freiburg

- FlowNet algorithm
- DeMoN algorithm
- DispNet algorithm
- DeepTAM algorithm

2.6 University of Groningen

- Place recognition algorithm and TB-Places data set
- Delineation algorithm (rose branches detection) and rose stems segmentation data set
- Push-pull layer for enhanced robustness of CNNs
- Stereo algorithm based on Max-Trees for embedded systems

2.7 Wageningen Research

- Trimming performance evaluation method
- Hedge and rose trimming tool design

2.8 Wageningen University

- Bush and hedge trimming path planning algorithms
- Visual feedback control methods for the robotic arm

3 Commercial Exploitation

3.1 Bosch

The results from the TrimBot2020 project can be exploited in two ways at Bosch. On the one hand, it is the exploitation by developing new product domains. On the other hand, it is the exploitation of components from TrimBot2020 in existing product domains, since Bosch is already present in several robotic domains such as service robots for indoor and outdoor use, intra-logistics robots or industrial robots. Figure 1 shows four examples of Bosch products from these domains.

(a)

(b)

(c)

(d)

Figure 1: Bosch robotic products. (a) Bosch Indego robotic lawn mower. (b) Bosch Roxxter robotic vacuum cleaner. (c) Bosch APAS automatic production assistant. (d) Bosch ActiveShuttle intra-logistics robot.

Within Bosch, the TrimBot2020 project is located in the strategic program Autonomous Systems and Robotics of the Corporate Research division. This program is in close cooperation with all business units relevant for robotics, e.g. Power Tools (including Home and Garden), Bosch Siemens Hausgeräte (BSH), Bosch Rexroth (Drive and Control Technology) and the Bosch Start-Up Platform Grow. Since the activities of the strategic program are regularly reported to these and all other interested business units, the results and findings from the TrimBot2020 project were reported to these business units. However, up to now no business unit has been found that wants to exploit the TrimBot22020 hedge and rose trimming robot directly. Therefore, other exploitation strategies such as the transfer to an existing robotic startup or the founding of a new garden robotic startup are also considered in this report. However, the main exploitation focus of TrimBot2020 results at Bosch is on the individual exploitation of algorithms, methods and data sets.

3.1.1 Exploitation of components in existing product domains

The concept of only using cameras for environmental sensing on an outdoor robot and so taking a completely new approach to a core component of robot navigation brought new and innovative approaches for visual perception. These approaches are in competition with traditional, lower-risk approaches used in current product development with a fixed time frame. The innovative vision based approaches developed in the TrimBot2020 project allow Bosch to make initial assessments for further development. These will be included in pre-development for next generation products. A detailed list of TrimBot2020 results exploited at Bosch follows in the next sections. They are grouped in three categories: Results which can be applied to all robotic applications in general, results which are particularly suitable for mobile robots and results which are particularly suitable in the garden domain.

Results exploitable by other robotic applications in general The results listed in this section are core components in the robotics domain and can therefore be exploited in robotics projects or products in general. However, they are not exclusively usable in the robotic domain and may also be exploited in other domains.

- The use of FlexBE (based on state machines) for behavioral modeling of a robot showed positive results and is now transferred to other projects within Bosch Corporate Research.
- The stereo camera system with integrated disparity calculation on an FPGA is suitable for all applications with limited resources (e.g. lawn mower or vacuum cleaner).
- The setup with 360° stereo cameras enables the same level of environment sensing as it is realized in traditional approaches mostly by expensive Lidar sensors. The stereo camera setup as it is used in TrimBot2020 provides an alternative for a surround view of coloured and grey scale images in addition to the depth information.
- Innovative approaches for calculating the depth information from stereo data (e.g. DispNet) can be exploited wherever more detailed depth information is necessary. For example, this can be used in industrial robots to sense objects with an accurate 3D shape. Initial tests were carried out to use DispNet with the data from an Intel RealSense camera mounted on an industrial robotic arm.
- The local 3D scene reconstruction using DeepTAM can be used for industrial robots like APAS to reconstruct their working space and especially support pick and place applications.

Results exploitable by mobile robots The engagement of Bosch in the domain of mobile robots has already created three successful products, the Indego robotic lawn mower, the Roxxter vacuum cleaner and the ActiveShuttle intralogistics robot. The results exploitable for mobile robots produced by Bosch are:

- The ground truth position recording technique for mobile platforms developed in TrimBot2020 has been transferred to other internal projects. Also the filters for ground truth position validation and the filters for orientation and position fusion are transferred to other internal projects.
- The data sets with ground truth robot poses used for the SLAM evaluation in the TrimBot2020 project were and will in the future be used for development and evaluation of SLAM algorithms.
- The Visual SLAM developed in the TrimBot2020 project is as SLAM in general a core component in robot navigation and therefore exploitable for all mobile robot activities within Bosch. The TrimBot2020 visual SLAM unfortunately did not achieve the required robustness or accuracy to be used directly in product development. Thus, further pre-development is needed to improve both accuracy and robustness.
- The experiences and also the implemented methods for robot navigation, including path planning and obstacle avoidance as applied in TrimBot2020, can be exploited in the further development of mobile robots.
- The implementation of an any-angle global path planner allows for example the production of meander patterns in grid based representations based on any angle. This helps a lot for meander navigation which is particularly advantageous for lawn mowers and vacuum cleaners.

Results exploitable in the garden domain Since the TrimBot2020 project deals explicitly with a robot working in a garden, there are of course results which are particularly suitable for an exploitation in this application domain. The most likely exploitation of these results will therefore be the further development of the lawn mower Indego.

- The semantic scene interpretation method from the TrimBot2020 project is optimized for garden features and is particularly suitable for the exploitation in the garden domain. Therefore, the semantic image segmentation method from UvA will be used as baseline for the development of further semantic segmentation algorithms usable on a robotic lawn mower.
- The semantic segmentation algorithm from UvA is also the basis for the development of object detection algorithms applied to gardens. Example object instances can be bushes, trees, lawn, houses, etc. In the future, this can then be integrated into robotic lawn mowers in order to improve obstacle avoidance as well as mapping and localization.
- Both semantically annotated image data sets (real/synthetic) from the "3D Reconstruction meets Semantics" workshops will be used in a pre-development project to develop and evaluate semantic and object detection algorithms.

- The pipeline for the semantic annotation of real image sequences based on an annotated point cloud of the environment and the known position of the robot (e.g. tracked by the ground truth position technique developed in TrimBot) will be used in future projects to label further images for the development of semantic segmentation and object detection methods.

3.1.2 Developing new product domains

The results from the TrimBot2020 project can be exploited within new product domains by either starting the development of a hedge trimming respectively rose cutting robot based on the TrimBot2020 prototypes or by transferring the results to start the development of a different and more general gardening robot. As safety and costs are still blockers from a current perspective, a pre-development study has first to be started to address these topics, before starting the development of a marketable product based on the TrimBot2020 prototypes is possible. However, due to the current economic situation and the focusing of Bosch robotics research on other topics such a pre-development study will not be started at the moment. Due to the good TrimBot2020 results and the fully functional prototypes, however, there is still the chance to start such a pre-development study in the future.

The second option to develop a more general gardening robot with less dangerous and simpler tools is therefore more obvious. For this purpose, the findings about a mobile platform carrying an arm are important results and can enable the development of a mobile gardening robot. However, development and manufacturing of a new product such as a gardening robot requires substantial financial resources. Due to the current economic situation there is no direct project funding within Bosch to realize such a product. However, there exist other possibilities to fund such activities within Bosch.

An alternative source for financing is provided by the Bosch Grow[1] platform that offers contests and provides time-limited financing for new products that have start-up-like characteristics. Grow is a Bosch internal incubator and platform for start-ups and intrapreneurs. They undertake the generic and administrative tasks and provide the infrastructure as well as an inspiring working environment and support new teams with methods and tools.

Another possibility is to transfer the results of TrimBot2020 to the currently existing Bosch start-up “Deepfield Robotics”[2]. This start-up currently works on small agricultural robots. Figure 2 shows one of their robots for mechanical weeding. Since their robots have a similar size to the TrimBot, they are particularly suitable for the utilization of TrimBot2020 results. With the results from TrimBot2020, Deepfield Robotics can on the one hand improve its existing agricultural robots, and on the other hand start the development of gardening robots that can open new markets for them. In addition to the agricultural domain, this can be a first step towards the market for professional gardeners.

[1] https://www.growplatform.com/about-grow/
[2] https://www.deepfield-robotics.com/en/

Figure 2: Prototype from Deepfield Robotics for mechanical weeding.

3.2 ETH Zurich

ETH Zurich team founded a start-up company, namely SkyAware, that produces the embedded camera systems based on the developed FPGA technology. SkyAware substitutes the initially planned Skybotix Ltd as provider of the camera system to the TrimBot2020 consortium, as Skybotix was bought by GoPro and stopped selling the sensors initially planned to be mounted on the robot. The core component of the camera system produced by SkyAware is a FPGA that synchronizes all cameras and computes depth maps for each stereo pair. The advantages of the sensor, namely its low-power consumption and easy integration via a USB port, will potentially make the system interesting for anyone in need of embedded multi-camera solutions, e.g. for drones and other type of robots. This includes both academic research labs as well as industrial companies. Skyaware sold its technology to Sevensene in 2018. Sevensense further develops the software and hardware of the camera setup to unlock novel applications on mobile robotics.

3.3 University of Amsterdam

The University of Amsterdam is exploring commercial exploitation of project results. Potential stakeholders for commercial exploitation:

- Enza Zaden: Enza Zaden develops new vegetable varieties that are grown, sold and consumed all over the world.
- Rijk Zwaan: A vegetable breeding company that creates value-added products and services.

3.4 University of Edinburgh

University of Edinburgh team do not anticipate any commercial exploitation results of the project.

3.5 University of Freiburg

The company Valeo is extending DeepTAM to autonomous driving application. The company IMRA is building on multi-hypothesis networks for probabilistic future prediction.

3.6 University of Groningen

University of Groningen team do not anticipate any commercial exploitation results of the project.

3.7 Wageningen Research

Wageningen Research do not directly exploit results commercially. However, they publish about the results in magazines, newspapers, radio, television and for the agricultural sector relevant exhibitions (e.g. Vision&Robotics, GreenTech).

The stakeholders are the general public, professionals like civic park gardeners, golf courses, large private estates, farmers, maintaining their fields and garden centers and machine builders and equipment suppliers for the agricultural sector.

These dissemination activities serve as a stepping stone to acquire future research and development projects, in different application domains (e.g. selective harvesting robots). Wageningen Research currently do not plan to file any patents because more benefit is expected from open publicity and writing scientific publications about it.

3.8 Wageningen University

14 companies financially support the FlexCRAFT program and are potential users of the developed technologies. This includes companies in the agri-food sector: Marel Poultry, Priva, Houdijk Holland, Blue Print Automation, RijkZwaan and CellerLand, and companies in the tech sector: ABB, Demcon, Festo, Maxon Motor, Protonic, Aris BV, 3DUniversum, and Cerescon.

4 Scientific and Academic Exploitation

4.1 Bosch

The Bosch team do not anticipate any scientific exploitation results of the project.

4.2 ETH Zurich

For the multi-camera SLAM and localization approaches, ETHZ a pure scientific exploitation is currently planned. Compared to other SLAM systems, the one developed in the TrimBot2020 project contains an online calibration component able to calibrate the extrinsic parameters of the multi-camera system. The inclusion of semantic image information into the localization method is under development and will increase the scientific dissemination and exploitation potential.

The ability for long-term localization is not only important in the context of the TrimBot2020 project but is also required in the context of self-driving cars as well as Augmented and Virtual Reality (e.g., the Augmented and Virtual Reality solutions offered by Google, Oculus, and Microsoft). Similarly, robust SLAM is also a prerequisite for these areas.

ETHZ expects that the results of the TrimBot2020 project will gather considerable interest in both academic and industrial research.

Possible stakeholders are:

- academic and industrial researchers in robotics, SLAM systems, 3D computer vision, localization system

Exploitation activities concern:

- publications and paper presentations at the top conferences in Computer Vision (CVPR, ICCV, ECCV) and Robotics (ICRA, IROS)

4.3 University of Amsterdam

The University of Amsterdam exploitable results are:

1. Intrinsic image decomposition algorithm: an end-to-end physics-based deep convolutional neural network model for intrinsic image decomposition of gardens.

2. Semantic segmentation algorithm: a new segmentation scheme combining different components such as detection, optical flow and segmentation for improved semantic labeling at the pixel.

3. Synthetic garden dataset: a largescale scene-level synthetic dataset with ground-truth images. The dataset will contain more than 112,000 images of gardens from more than 90 different scenes with 5 different lighting conditions; clear sky, cloudy, overcast, sunset and twilight. All scenes contain natural common garden proto-objects, such as grass, pavement, hedge, topiary, rock, fence and tree.

Exploitation activities concern:

- publications at top conferences in Computer Vision (CVPR, ICCV, ECCV) and journals (IEEE TIP, IEEE PAMI, IJCV).

4.4 University of Edinburgh

A tool for Ground Truth semantic annotation ROSEMAT of video sequences was designed to work directly with data recorded by multi-camera system mounted on a robot ("rosbags"). It can transfer semantic labels from a 3D semantic model of the scene to 2D images and also transfer labels between consecutive video frames.

Natural outdoor datasets feature synchronized video streams from multiple cameras mounted on a robot navigating around gardens in different scenarios, along with position and orientation tracking and semantic annotation of selected frames. 3D information of the scene is also provided from both robot-mounted and stationary laser scanners, the latter in the form of a semantic point cloud.

Point cloud registration allows creating accurate 3D registration of multiple point cloud, for the purposes of relative pose refinement and reconstruction. This is a general method which can be used in a variety of applications, particularly those requiring high accuracy. Extensive optimisation (by RUG) allows use also in interactive applications.

Visual servoing techniques developed for the rose pruning pipeline in TrimBot2020 were also used in a robot assistant project (at Living Lab in Edinburgh), which has produced a conference publication. Possible identified stakeholders are:

- researchers preparing semantic datasets
- researchers in the areas of 2D/3D scene understanding, 3D reconstruction

Exploitation activities concerned:

- release of the source code packages to the public (`https://github.com/rtylecek/rosemat`, `https://github.com/Canpu999/DUGMA`)
- release and archival of the dataset to the public (`https://gitlab.inf.ed.ac.uk/3DRMS/Challenge2018`)
- dissemination and contact with stakeholders through the presentation in a journal (Sensors[3], Remote Sensing) and conference articles (3DV[4], ECCV2018[5], IROS[6])
- workshop participations (3DRMS - ICCV2017, ECCV2018)

[3] https://www.mdpi.com/1424-8220/18/7/2249
[4] https://ieeexplore.ieee.org/document/8491030
[5] https://link.springer.com/chapter/10.1007/978-3-030-11015-4_48
[6] https://ieeexplore.ieee.org/document/8593652

4.5 University of Freiburg

FlowNet 2.0 is the first optical flow approach based on deep learning that reaches state-of-the-art accuracy. At the same time, it is by a factor of 100 faster than previous state-of-the-art techniques. This allows for reliable motion estimation at interactive frame rates. DeMoN is the very first work that formulates the problem of joint ego-motion and depth estimation as a pure learning problem. Given two images from a single moving camera, DeMoN can estimate depth and camera motion at interactive frame rates.

Exploitation activities concern:

- publications and paper presentations at the top conferences in Computer Vision (CVPR, ICCV, ECCV) and Robotics (ICRA, IROS)

4.6 University of Groningen

The University of Groningen team plans to exploit the activities and the scientific results by presenting them in journals and conferences on computer vision, image processing and pattern recognition.

A method for visual place recognition for mobile robotics based on a convolutional neural network embedding, effective even under severe appearance changes, was developed. The knowledge acquired for the development of this method is being exploited for adaptation of the approach to garden environments, for garden place recognition and for robot localization. A new data set for place recognition in gardens (formulated as an image recognition problem) was released. A method for segmentation of fine (elongated) structures in images was developed and published in a top-tier journal. Release of code and a new data set of rose stems with manual segmentaiton is ongoing. A new type of layer for CNNs was developed. Experiments demonstrated that this layer provide existing networks with enhanced robustness to corruptions and perturbations of input data, making them generalizing better to changing environemnts. A new algorithm for stereo matching designed for embedded systems taking into account a trade-off between resource efficiency and accuracy was also developed. This is being exploited by releasing the code and the ROS implementation.

Possible stakeholders are:

- researchers working on place recognition (in various applications) and robot localization
- researchers working on image processing and fine-structure segmentation problems
- researchers in machine learning and computer vision working with CNNs

Exploitation activities concern:

- dissemination and contact with stakeholders through presentation in journal (IEEE Access: `https://ieeexplore.ieee.org/document/8719902` and `https://link.springer.com/chapter/10.1007/978-3-030-29888-3_26`) and conference (`https://ieeexplore.ieee.org/document/8698240`) articles, workshop/conference participations, ResearchGate, websites (consortium and personal). Other papers are currently under review.

- release of the source code and developed datasets:
  - TB-Places data set: https://github.com/marialeyva/TB_Places
  - MTStereo algorithm for stereo vision: https://github.com/rbrandt1/MaxTreeS

4.7 Wageningen Research

WR plans to exploit the activities and the scientific results by presenting them in journals and conferences related to agro-robotics e.g. about the novel bush trimming evaluation method or structured design methods for developing robotic end-effectors. Furthermore, contributions to the ROS (Robot Operating System) community are planned to be carried out: e.g. a visual feedback controlled coverage path planning module.

Possible stakeholders are:

- the scientific community as well as the companies attending conferences in which the results will be presented.

4.8 Wageningen University

Exploitable results:

- Bush and hedge trimming path planning algorithms
- Visual feedback control methods for the robotic arm
- Trimming performance evaluation method
- Semantic SLAM
- Semantic scene reconstruction

The above-mentioned results of the TrimBot2020 project will be used and further developed in the NWO-program FlexCRAFT (Nov 2019 - Nov 2023). With five Dutch universities, a total of 10 PhD students and 3 postdocs will focus on the further development of core robotic technologies to advance robotics in the agri-food sector. Research will be done on four core technologies: (i) active perception, (ii) semantic world modelling, (iii) learning and control, and (iv) gripping and manipulation. These will be integrated in three use-case demonstrators on (a) greenhouse robotics, (b) food-processing robotics, (c) food-packaging robotics. The results of TrimBot2020 will mainly contribute to i, ii, iii, and a.

