TrimBot2020 Deliverable D7.3

Component and System Evaluation Plan

Principal Author: UEDIN
Contributors: UEDIN
Dissemination: PU

Abstract: This document specifies the methodology, measures and parameters for evaluation of the TrimBot2020 system and its components as specified in the previous D7.1. This document defines a set of performance measures (such as position, orientation and shape accuracy, speed, repeatability) for each component or a set of related components. Where applicable we propose a set of experiments to assess that component's performance. A similar set of performance measures is defined for the system as a whole.

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1 Physical components and control

Functionality of individual hardware components will be assessed by performing practical trials covering their operational range based on random or predefined sequences of actions.

1.1 Vehicle platform

Developed in WP1 - Mobile platform.

1.1.1 Vehicle base

Standalone robot base. *Developer*: Bosch.

- Random driving trials with expected payload
  - drives at least 10 m distance on selected surfaces in test garden: grass, pavement
  - drives at least 1 m up and down 10° sloped grass
  - drives at least 1 m along and across 10° sloped grass
  - both forward and backward
  - minimum turning radius 1 m
- Provides uninterrupted power supply to all system components (sensors, drives, manipulator, end-effectors, controllers etc.) for at least 20 minutes

1.1.2 Mounted base

Vehicle base with mounted arm and clipper. *Developer*: Bosch.

- Drive 3 m on a straight path on flat even surface
  - evaluate *cross track error* (XTE) from a straight line
    - allow 30 mm on solid surface
    - allow 50 mm on grass
  - arm in stable position and clipper not activated
  - open loop control

1.2 Arm with clipper

Developed in WP2 - Manipulator construction and control.

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1.2.1 Robotic arm

Commercial robotic arm with 6 DOF. *Developers:* WUR, Bosch.

- 6 DoF positioning within 0.5 m from the robot base
  - at maximum permitted extension
  - with trimming tools mounted
  - does not cause robot to fall over when mounted and interacting with the vehicle
- Repeatability on tool center point (ISO 9283, [3])
  - positioning 3 mm
  - orientation 5°
  - everywhere in the workspace
  - evaluated using laser tracker and high-precision IMU
- Can traverse a straight path
  - XTE below 4 mm

1.2.2 Rose clipping tool

Custom designed clipping tool. *Developer:* DLO.

- Can cut through 10 mm thick rose stem
- Shape allows to reach the positions to cut branch
- Able to cut branches with an accuracy of 10 mm on the stem

1.2.3 Hedge trimming tool

Custom designed trimming tool. *Developer:* DLO.

- Does not get stuck in boxwood overgrown up to 40 mm from the desired shape
- Can cut through 5 mm thick boxwood branch
- Able to cut surfaces with an accuracy lower than 5 mm
- Must be able to cut 95% of the overgrown branches

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1.3 Visual sensors

Developed as a part of WP3 - 3D acquisition and fusion. Consists of two sets of stereo cameras for sensing of the environment, one mounted on the vehicle and second on the arm. *Developer:* ETHZ.

- Provides uninterrupted video stream
  - simultaneously 10 cameras
  - full 360° composed field of view
  - at least 270° stereo coverage
  - at least 5 fps WVGA resolution
  - maximum 200 ms capture latency
- Objects in the range 0.1 m to infinity are in focus
- Handles back-light well
  - no flooding present
- Handles changing outdoor light conditions well
  - exposure changes smoothly
  - no flickering present
- Sensor chip is free from dirt
- Lenses are initially clean
- At most few hot or cold pixels
  - test images of uniform white background
  - test images with covered lens
- Accuracy of the pentagonal ring setup
  - Angular error of the camera arrangement $<1^\circ$

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2 Computational components

We will perform essential unit testing of software components and packages. We will use both simple synthetic test inputs and real data input captured in our test garden. The produced output will be compared with expected output (based on synthetic or GT model) and the discrepancy will be measured as specified for individual components below.

Evaluation measures for real input are dependent on recorded ground-truth (GT) data, which include

- synchronized color video streams from cameras,
- motion logs for robot positions from laser tracker,
- 3D data stream from mounted laser scanner,
- high-precision scene 3D model from stationary scanner.

These will be in detail described in deliverable D7.4 - *Ground-truth data definitions and acquisition*.

The project will provide shared code repository (GitLab CE server[1]), which supports continuous integration and test automation (GitLab CI[2]). This will allow partners to implement and run evaluation of their components in a standardized framework.

2.1 3D data processing

Developed in WP3 - 3D acquisition and fusion.

2.1.1 Garden 3D data surface extraction and fusion

Process sensor data from vehicle cameras and maintain 3D representation. *Developer:* UEDIN.

- Can sense environment in the range of 0.2 m to 20 m from the current location
- Absolute accuracy of acquisition and fusion of 3D data:
  - 10 mm RMS accuracy on flat textured test objects within 1 m of vehicle
  - measure fused geometry against GT geometry
  - mean nearest neighbor distance between point clouds or mesh faces (assuming statistically comparable sampling)
- Relative accuracy of 3D data w.r.t. vehicle cameras
  - stereo, scene flow and SfM fused

[1]Stand-alone Community Edition distribution, https://gitlab.com/gitlab-org/gitlab-ce.
[2]Continuous Integration component, https://about.gitlab.com/gitlab-ci.

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- relative error e_{rel} of depth map d is calculated as

$$e_{rel} = \frac{|d - d_{GT}|}{\frac{d_{GT}^2}{bf}}, \tag{1}$$

  where d_{GT} is the depth according to GT scan, b is the camera baseline and f is the focal length (in pixels); then e_{rel} measures effective matching error in pixels [2]
- maximum relative error allowed $e_{rel} < 1$

- Test with planar textured surface
  - 10 mm accuracy at 1 m distance from camera
  - 30 mm accuracy at 3 m distance from camera

2.1.2 Local 3D data surface extraction and fusion

Process sensor data from arm cameras. *Developer:* ALUF.

- Can sense environment in the range of 0.1 m to 2 m from the current arm position
- Absolute accuracy of acquisition and fusion of 3D data:
  - 2 mm RMS accuracy on flat textured test objects within 1 m of arm end point
  - measure is the same as in the previous section
- Relative accuracy of 3D data w.r.t. arm cameras
  - stereo and scene flow fused
  - maximum relative error allowed $e_{rel} < 1$
- Test with planar textured surface
  - 2 mm accuracy at 0.2 m distance from camera
  - 10 mm accuracy at 1 m distance from camera

2.1.3 3D to map deformable registration algorithm

Register the sketch with measured 3D data. *Developer:* UEDIN.

- Calculate mean and maximum residual error after registration
  - ground surface control points error < 50 mm
  - map object locations and shape parameters error < 50 mm
  - map object shape parameters error < 20 mm

2.2 3D data analysis

Developed in WP4 - 3D data analysis and scene understanding and WP5 - Dynamic reconstruction for planning and visual servoing.

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2.2.1 Garden object detection algorithm

Analyze scene based on 3D data. *Developer:* UVA.

- Object detection accuracy (3D)
  - measure position against GT object
  - calculate Mean Average Best Overlap (MABO [1]):
    - evaluates overlap between 3D bounding boxes based on intersection-over-union
    - MABO at least 0.5 required
- Drivable region localisation (2D)
  - ground surface segmentation (binary):
    - 0.1 m accuracy
    - max. distance of a mislabeled site to the border of its GT region
- Semantic accuracy
  - Data-driven
    - compare result of classification with GT annotations in a confusion matrix
    - global average accuracy: at least 0.6 Mean Average Precision (MAP)
    - class average accuracy: at least 0.55 MAP
    - count and minimize undesirable confusions:

Super-class		Driv.	Non-Driv.	Trim.	Non-trim.
Ground	drivable		X	X	X
	non-drivable	X		X	X
Object	trimmable	X	X		X
	non-trimmable	X	X	X	

    - Super-class accuracy: MAP at least 0.95 = X
    - *Ground*: grass, mulch, pebbles, etc.
    - *Trimmable objects*: hedge, topiary, rose bush, etc.
      - within this super-class additionally:
      - semantic label average accuracy: at least 0.8 MAP
      - shape label average accuracy: at least 0.6 MAP
    - *Non-trimmable* objects: bench, fence, obstacles, etc.
  - Model-driven
    - result of data-driven detection combined with the semantic sketch map and vehicle localization
    - global average accuracy: at least 0.85 MAP

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2.2.2 Cutting surface and stem extraction

Localize clipping and cutting sites. *Developer:* ALUF.

- Localisation accuracy
  - measure position and shape against GT object
  - bush: 10 mm RMS accuracy on cut bush surface
  - rose: 5 mm stem localisation accuracy

2.2.3 Semantic SLAM and relocalisation

Developers: ETHZ.

- Vehicle localization accuracy
  - maximum 0.1 m error from GT position
  - maximum 10° error from GT orientation
- Obstacle map accuracy
  - 50 mm occupancy grid accuracy
  - max. distance of a mislabeled site to the border of its GT region

2.2.4 Arm localisation

Developer: WU, ETHZ.

- Arm end point localization accuracy
  - distance from a known fixed point
  - global 0.1 m map-based accuracy from GT position (initialized from SLAM)
  - local 5 mm accuracy relative to arm end
  - maximum 10° error from GT orientation

2.3 Task specification and planning

These components (WP1 and WP2) will be initially tested with the Gazebo simulator[3]. It is a 3D dynamic simulator with the ability to accurately and efficiently simulate robots in complex indoor and outdoor environments. While similar to game engines, Gazebo offers physics simulation at a higher degree of fidelity, a suite of sensors, and interfaces for both users and programs.

[3] http://gazebosim.org/

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2.3.1 User sketch map and interface

Digital sketch map of the garden. *Developer:* UEDIN.

- All garden objects modellable
- Set of published map objects visualized in RViz corresponds to the user map
- Click to known location in the map publishes correct coordinates
- Click at map object successfully identifies and publishes corresponding garden object

2.3.2 Navigation and trimming planning

Cutter path planning including extended surfaces like long boxwood hedges. *Developer:* Bosch, DLO, WU.

- Trimming plans and their execution (Sec. 2.4) will be evaluated together
- The plan will be visualized in the garden user interface and manually inspected by the testing user for viability and efficiency
- Accurate robot servoing to target plants
  - base follows hedge with 50 mm RMS relative position at 100 mm offset
- Successful bush trimming
  - 10 mm local variation from plan
    - ∗ calculate RMS distance between points scanned with laser scanner after trimming and the desired shape
    - ∗ desired shape is represented by surface in a sketch map, fitted to the trimmed shape, i.e. the location is relative
  - cut full surface and initial striping
  - cut from 20 mm outgrowth
  - cut from 40 mm outgrowth
  - different shapes: flat side, curved (cylindric) side, sphere
- Successful rose clipping
  - 10 mm distance from specified location

2.3.3 Master controller

High level task management. *Developer:* Bosch.

- Successful coordination of tasks
  - including extended hedge trimming from multiple positions

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2.4 Action execution

Developed in WP1 and WP2.

Synthetic tests will be also performed with the Gazebo simulator.

2.4.1 Navigation execution

Calculates a path to reach a given destination and commands the vehicle to move along this path. *Developer:* Bosch.

- Random route following trials
  - maximum 50 mm RMS cross track error (XTE) from the given route
- Successful map-based garden navigation to a particular location
  - 100 mm map-based location accuracy,
  - 100 mm location repeatability
  - 5° map-based orientation accuracy
  - 5° orientation repeatability
  - mean time to collision or blockage $>$ 5 min of operation
- Navigation errors are additional to the localization error (Sec. 2.2.3)
- Errors are measured relative to the center of rotation (COR) of the robot

2.4.2 Vehicle control

Controls the vehicle base by velocity commands and provides wheel odometry and IMU data. *Developer:* Bosch.

- Verify actions and IMU data received during different movements correspond to the manual input
- Use the joypad to control the robot

2.4.3 Trimming arm control

Cutter path execution. *Developers:* WUR.

- Accurate clipper servoing to target plants
  - random target object surface touching
  - clipper follows trimmed hedge at 10 mm offset on a given path
    - allow 5 mm RMS cross track error (XTE)
  - surface shapes: flat hedge, curved hedge, sphere

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3 Full system

The evaluation of the complete system is based on the combined demonstrator plan D7.2 for mobile vehicle localisation and clipping.

3.1 Evaluation procedure

1. Place vehicle in the test garden
2. Vehicle surveys garden under user control using the sketch map, with collision protection, and displays recovered 3D scene
3. User specifies cutting location and action for
   (a) single rose bush
   (b) single flat boxwood bush
   (c) straight ivy hedge
   (d) curved and flat boxwood hedge
4. Vehicle navigates with collision avoidance to cutting locations
5. Platform performs cutting actions

Concrete locations and target objects will be specified in the garden map.

3.2 Measures

Success criteria are met if measures given in Sections 1 and 2 are satisfied for all tasks, i.e.

- Vehicle can stably carry arm on a variety of surfaces
- Arm/clipper can locate and cut rose stems and trim bush surfaces
- Vehicle can plan and execute servo motions to get near to several sides of target plants
- Vehicle/clipper can maintain surface flatness
  – goal accuracy of 10 mm over extended trimmings
- Interactive operation speed, i.e. near real-time, maximum 1 sec delays

References

[1] J.R.R. Uijlings, K.E.A. van de Sande, T. Gevers et al. Selective Search for Object Recognition. IJCV (2013) 104: 154.

[2] X. Hu and P. Mordohai. A Quantitative Evaluation of Confidence Measures for Stereo Vision. PAMI (2012) 34: 11, pp. 2121-2133,

[3] Martin Jägersand, Olac Fuentes, Randal C. Nelson. Experimental evaluation of uncalibrated visual servoing for precision manipulation, ICRA (1997)

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