DARPA SubT STIX Qualification Submission: CTU-CRAS

Karel Zimmermann[1,*], Vojtěch Šalanský[1], Martin Pecka[1], Tomas Svoboda[1], Martin Saska[1], Vojtěch Spurný[1], Tomas Báča[1], Matej Petrlík[1], Tomas Krajník[1], Tomas Rouček[1], Jan Faigl[2], Jan Bayer[2], Petr Čížek[2], Miloš Prágr[2], Francois Pomerleau[3], and Vladimír Kubelka[3]

[1]Czech Technical University in Prague, Department of Cybernetics
[2]Czech Technical University in Prague, Department of Computer Science
[3]University of Laval, Canada
[*]zimmerk@fel.cvut.cz
[1]all authors contributed equally to this work

ABSTRACT

This is the STIX qualification submission of the CTU-CRAS team. It demonstrates required capabilities for two tracked robots equipped by flippers, one small hexapod and one mid-size quadcopter. The organization of the document strictly follows qualification guidelines. Demonstrated systems do not use any GPS-sensor or GPS-based navigation.

Part 1: Team Information

- Team Name: CTU-CRAS
- Team Organization: Czech Technical University in Prague, Center for Robotics and Autonomous Systems
- Organization Location(s): Czech republic
- Team Point-of-Contact: Karel Zimmermann, zimmerk@fel.cvut.cz, +420 777882256
- List of all team members and their affiliations:
  - Karel Zimmermann, Czech Technical University in Prague, Department of Cybernetics
  - Vojtech Šalanský, Czech Technical University in Prague, Department of Cybernetics
  - Martin Pecka, Czech Technical University in Prague, Department of Cybernetics
  - Tomáš Svoboda, Czech Technical University in Prague, Department of Cybernetics
  - Martin Saska, Czech Technical University in Prague, Department of Cybernetics
  - Vojtech Spurný, Czech Technical University in Prague, Department of Cybernetics
  - Tomas Báča, Czech Technical University in Prague, Department of Cybernetics
  - Matej Petrlík, Czech Technical University in Prague, Department of Cybernetics
  - Tomas Krajník, Czech Technical University in Prague, Department of Computer Science
  - Tomas Roucek, Czech Technical University in Prague, Department of Computer Science
  - Jan Faigl, Czech Technical University in Prague, Department of Computer Science
  - Jan Bayer, Czech Technical University in Prague, Department of Computer Science
  - Petr Čížek, Czech Technical University in Prague, Department of Computer Science

- Miloš Prágr, Czech Technical University in Prague, Department of Computer Science
- Francois Pomerleau, University of Laval, Canada
- Vladimír Kubelka, University of Laval, Canada

Part 2: Technical Approach (500 words max per sub-section)

Figure 1. UGV-VRAS robot: tracked-robots equipped by flippers (left), its sensor suite (middle) and human interface (right).

Figure 2. UGV-Cameleon robot: Operating in adverse conditions (fog, gale, night).

Figure 3. UGV-Hexapod robot: Operating in different terrrains.

Autonomy: high-level software architecture, human interfaces

High-level software architecture: The software architecture is based on the Robot Operating System (ROS). The high-level planning for the multi-robot search & rescue task, will be based on the system [1], which we have successfully used to win the Mohamed Bin Zayed International Robotics Challenge 2017 [2].

Human interface is based on RVIZ/RQt visualization tool, see Figure 1-right for details. Human interface allows to control the pan-tilt thermal camera, virtual PTZ camera sythetized from panoramic ladybug images and visualize 3D point cloud map with detected artifacts. There are three different motion control modes: (i) manual, which allows the full control of tracks and flipper using a gamepad, (ii) semi-autonomous, which allows to control the speed, while flippers are controlled autonomously and (iii) fully autonomous, where the robot is controlled autonomously toward waypoints. Waypoints are provided either by the human operator or by the high-level planning system.

Figure 4. UAV-Quadcopter:

Mobility: number of platforms, types of platforms, fuel sources, safety considerations

Our robotic team consists of three Unmanned Ground Vehicles (UGV-VRAS, UGV-Cameleon and UGV-Hexapod) and one Unmanned Aerial Vehicle (UAV-Quadcopter), see Figure 1 for details. Two UGVs are tracked robots equipped by flippers, which provide additional support during the traversal of a rough terrain. The third UGV is a small hexapod. All platforms are powered from the on-board batteries. Heavier ground platforms such as UGV-VRAS and UGV-Cameleon are equipped by emergency stop buttons mounted on the robot body. Since different hardware architectures and sensor suites require to use different approaches, the following sections are divided into four subsections describing the robot-specific approaches explicitly.

UGV-VRAS:
This is a tracked robot equipped by four independently controlled auxiliary subtracks (flippers). The sensory suite consists of (i) the Point Grey Ladybug 3 panoramic camera providing RGB images, (ii) the SICK LMS-151 laser scanner on a rotating mount providing 3D pointclouds and (iii) the thermal camera Micro-Epsilon thermoIMAGER TIM 160 mounted on a pan-tilt unit providing thermal images, (iv) Xsens MTi-G Inertial Measurement Unit providing angular velocities and linear acceleration and (v) sensor capable of detecting smoke and flammable gasses.

UGV-Cameleon:
The Cameleon robot, produced by ECA robotics, is a rugged modular platform intended for security applications such as counter-IED, bomb disposal and infrastructure protection, see Figure 2 for details. Our team uses the robot primarily for experiments relevant to visual navigation in adverse environmental conditions. The robot is equipped by two independently-controlled tracks, two jointly-controlled auxiliary flippers, two night vision cameras and an ROS-compatible embedded PC with long-range WiFi transceiver. The robot allows to mount superstructures with several sensory pods, and a typical sensory suite consists of stereo- and RGB-D cameras, UWB radars and laser rangefinders. To allow operation in low-visibility conditions, the robot is equipped with 4000 lumen flashlight.

UGV-Hexapod:
The hexapod robot consists of six legs attached to the trunk which hosts the battery power source, sensors, and the main computational platform. Each leg has three joints actuated by the Dynamixel AX-12A actuators that provide feedback of their current position. The position feedback of the servos is used in the adaptive locomotion [3] that allows the robot to traverse rough terrains and augments tactile sensing to the robot (see Figure 3). The used battery pack is 3 Cell 8000 mAh battery pack, that provides the robot with up to 3 hours of operation. The robot is equipped with the attitude and heading reference system XSense MTi-30 which provides the robot with the acceleration, gyroscopic, magnetometric and fused orientation readings. As the main exteroceptive sensor, the robot is equipped with the RGB-D Intel RealSense D-435 camera, the camera provides RGB image and depth image calculated from an infrared stereo camera pair. In low visibility conditions, the camera uses built-in projector to project an infrared pattern in front of the robot. The main computational platform of the robot is the Intel NUC with the Intel Core i7-8650U processor and 8GB of RAM.

UAV-Quadcopter:
The main structure of UAV consists of a DJI hexacopter F550 frame and E310 DJI motors, see Figure 4 for details This choice satisfies the size limitations of the event and the payload capability that is necessary for additional sensors. The flight time of this UAV platform with fully charged 4 cell batteries with 6750 mAh capacity is up to 15 minutes. The system is controlled at the lowest level by a PixHawk flight controller that contains a set of sensors, such as accelerometers, gyroscopes, and magnetometers, which are necessary for stable UAV flight. During an autonomous flight, the flight controller is commanded by a controller inside of an onboard PC Intel NUC-i7. This PC also provides sufficient computation power to solve UAV coordination, state estimation, and motion planning in the complex environment. All these subtasks are done using data obtained by onboard sensors that in our case are 2D 360 laser range scanner SLAMTEC RPLIDAR A3M1, laser rangefinder Garmin-Lite V3, onboard camera mvBlueFOX-MLC200wG, and a ring of 8 rangefinders called TeraRanger Tower Evo.

The autonomous flight of the UAV can be stopped by calling land routine just by pressing the button on a joystick, or by sending a command in a terminal on the basestation pc. Furthermore, the pilot can anytime for safety reason switch the autopilot into manual control using RC transmitter to retake the control. Finally, the UAV will be expanded with a propeller guard during the final event.

Perception: sensors, software, degraded sensing approach

Perception-UGV-VRAS:

Artifact detection: Since the exact list of artifacts to be used in particular circuits is not yet known, we have focused on the detection of (i) humans, (ii) backpacks, and (iii) gas leakage. Submitted qualification video uses YOLO-like network architecture tuned on our own RGB images captured from the on-board-only-illuminated environment. We are recently integrating our multi-modal human detection approach [4], which will make use of the actively controlled pan-tilt thermal camera to provide more accurate detections in poorly illuminated areas. The robot is equipped with a sensor module capable of detecting smoke and flammable gasses. There are three individual sensors in this module. Smoke is detected by a standard optical smoke detector which outputs logical levels indicating presence of smoke. The MQ-2 sensor (sensitive to methane, butane, and LPG) works together with the MQ-3 sensor (sensitive to alcohol, ethanol) to detect presence of flammable gasses. The MQ-2 and the MQ-3 sensors output analog value, it is therefore possible to express the concentration of detected gasses in ppm. Position in the world coordinate frame at which the gas leakage was detected is marked in the 3D map.

Localisation and mapping algorithm fuses measurements from several different types of sensors: (i) inertial measurements unit measured at 80Hz, (ii) track odometry provided at 15Hz, (iii) 3D point-cloud measured by the laser scanner at 0.3Hz. Robot position is first estimated independently from each type of sensor. The 3D pointcloud localisation is estimated by ICP algorithm [5]. Individual position guesses are then fused by our EKF-based fusion algorithm [6]. Resulting 3D pointcloud map is further used for the artifact localisation and motion control and high-level planning. We plan to enhance the 3D map based on our deep 3D mapping pipeline [7].

Path-execution and autonomous flipper control on a rough unstructured terrain is based on our current work [8]. This method combines real-world and Gazebo-simulated trajectories to learn the flipper-control policy via the novel guided reinforcement learning approach. The policy is convolutional network, which maps local height map, pitch and roll on flipper control signals.

Perception-UGV-Cameleon:

Since the Cameleon UGV can carry the same sensors as the UGV-VRAS robot, it is possible to deploy the same navigation and SLAM methods as in the previous case. However, the robot was primarily used to evaluate vision-based navigation methods and thus, we aimed to demonstrate its ability to navigate using monocular vision and on-board lights only. The navigation method, shown in the videos, is based on our previous research on reliable long-term navigation [9, 10, 11]. During the challenge, this method would allow a robot to re-trace it's original path or to navigate to a given location using a memory-efficient map created by another UGV or UAV.

Perception-UGV-Hexapod:

The control architecture follows the traditional hierarchical paradigm with pipeline of sensing, planning and acting. The RGB-D camera is used as the main exteroceptive sensor, that provides the robot with color images and depth images, which are used in the localization and mapping nodes. The localization is achieved using the modified version of the simultaneous localization and mapping approach ORB-SLAM [12] which provides the localization information to the robot in 6 degrees of freedom. The mapping node fuses the localization and individual depth images into the probabilistic elevation map, which is constructed with the maximum z-coordinate assumption [13] and each scan is filtered using the shadowing filter for outliers. Afterwards, the map is passed to the path planner that takes the desired goal location on the input and it plans the path towards the goal, which is passed to the planner as the desired location in the map selected by the robot operator. The robot is trying to reach the desired goal location while exploring the environment and looking for the way towards its target. The resulting plan is passed to the trajectory tracker, which guides the robot along the path. The replanning is performed whenever the newly updated cells in the map interfere with the planned path. On the bottom level, there is the adaptive locomotion controller [3], that utilizes feedback from the joint actuators to allow the platform rough terrain traversing. Underground, areas with low to no visibility can be expected, therefore we aim to utilize the complex hexapod robot tactile sensing in areas with degraded visibility for topo-metrical exploration and localization. Further, we will use terrain-aware planning to assess terrain traversability [14] and adjust the robot path and locomotion style accordingly.

Perception-UAV-Quadcopter:

A state estimate is needed to control the UAV autonomously. The state estimation is based on a Kalman Filter that fuses measurements from available sensors to achieve a reliable and robust state estimate that can stabilize the UAV. Measurements from accelerometers, barometer, and a downward-facing laser rangefinder contribute to the estimate of the UAV height above the ground. For estimating the lateral state variables, we use the optical flow calculated from the image stream of a downward facing camera. The implementation of the optical flow algorithm is based on FFT and RANSAC as described in [15]. The calculated optical flow is transformed into the velocity of the UAV using known height above the ground and known camera calibration. This velocity is fused with measurements of UAV tilts to provide a smooth state estimate suitable for the SO3 controller [16]. The setpoints for the controller are provided by Model Predictive Control (MPC) Tracker [17] that shapes the reference trajectory to satisfy constraints and physical limitations of the platform.

When flying in difficult lighting conditions, the velocity is alternatively estimated from an algorithm based on Iterative Closest Points.

Networking: hardware, software, radio frequency spectrum

The UGV-VRAS vehicle's communication abilities were thoroughly tested throughout the TRADR project [18] (*Long-term human-robot teaming for robot assisted disaster response*). Many radio technologies were tested for high-bandwidth communications, however the most suitable and reliable showed to be 5 GHz WiFi PtP links. Such links provided live video with a delay of few seconds for distances up to 110 yards in an old steelworks full of iron struts and rebars. For cases when the robot is supposed to leave the WiFi-covered area, it can be equipped with a low-bandwidth 868 MHz radio link that allows basic monitoring and control of the vehicle (without live video or maps).

Part 3: Demonstration Videos

Videos-UGV-VRAS:
Mobility:

- https://www.youtube.com/watch?v=5vCXAX4ZK_0
- https://www.youtube.com/watch?v=R3JZtWXMdyc

Artifacts:

- https://www.youtube.com/watch?v=0WxoYRXkZO0
- https://www.youtube.com/watch?v=NDMqBwO2oNA

Emergency stop:

- https://www.youtube.com/watch?v=U6PsZxdb2eY

Videos-UGV-Cameleon:
Artifacts and mobility:

- https://www.youtube.com/watch?v=-FTYHTdCAcc

Emergency stop:

- https://www.youtube.com/watch?v=HUPzwuBXSks

Videos-UGV-Hexapod:
Mobility:

- https://youtu.be/SEzT2PLvo-o
- https://www.youtube.com/watch?v=y7BmAhhsrbU&t=1s

Emergency stop:

- https://youtu.be/Rnilq9EyNwg

Videos-UAV-Quadcopter:
Mobility:

- https://www.youtube.com/watch?v=FmUcBu0su1s

Take off - emergency stop:

- https://www.youtube.com/watch?v=FjEkgSdZKcI

References

1. Faigl, J., Vana, P., Penicka, R. & Saska, M. Unsupervised learning based flexible framework for surveillance planning with aerial vehicles. *J. Field Robotics (JFR)* (2018).

2. Mohamed bin zayed international robotics challenge (mbzirc) (2018).

3. Mrva, J. & Faigl, J. Tactile sensing with servo drives feedback only for blind hexapod walking robot. In *International Workshop on Robot Motion and Control (RoMoCo)*, 240–245 (2015).

4. Petricek, T., Salansky, V., Zimmermann, K. & Svoboda, T. Simultaneous exploration and segmentation for search and rescue. *J. Field Robotics (JFR)* (2018).

5. Pomerleau, F., Colas, F., Siegwart, R. & Magnenat, S. Comparing icp variants on real-world data sets. *Auton. Robots (AR)* (2013).

6. Kubelka, V., Reinstein, M. & Svoboda, T. Robust data fusion of multimodal sensory information for mobile robots. *J. Field Robotics (JFR)* (2015).

7. K.Zimmermann, T.Petricek, V.Salansky & T.Svoboda. Learning for active 3d mapping. *Int. Conf. on Comput. Vis. (ICCV) - oral* (2017).

8. Pecka, M., Zimmermann, K. & Svoboda, T. Data-driven policy transfer with imprecise perception simulation,. *Int. Conf. on Intell. Robots Syst. (IROS) Robotics Autom. Lett. (RA-L)* (2018).

9. Krajník, T. *et al.* Simple yet stable bearing-only navigation. *J. Field Robotics* **27**, 511–533 (2010).

10. Krajník, T., Cristoforis, P., Kusumam, K., Neubert, P. & Duckett, T. Image features for visual teach-and-repeat navigation in changing environments. *Robotics Auton. Syst.* **88**, 127–141 (2017).

11. Krajnik, T. *et al.* Navigation without localisation: reliable teach and repeat based on the convergence theorem. In *IROS* (2018).

12. Mur-Artal, R. & Tardós, J. D. Orb-slam2: An open-source slam system for monocular, stereo, and rgb-d cameras. *IEEE Transactions on Robotics* **33**, 1255–1262 (2017).

13. Čížek, P., Masri, D. & Faigl, J. Foothold placement planning with a hexapod crawling robot. In *IEEE International Conference on Intelligent Robots and Systems (IROS)*, 4096–4101 (2017).

14. Prágr, M., Čížek, P. & Faigl, J. Cost of Transport Estimation for Legged Robot Based on Terrain Features Inference from Aerial Scan. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 1745–1750 (2018).

15. V.Walter, T. & M.Saska. Self-localization of unmanned aerial vehicles using onboard sensors, with focus on optical flow from camera image. In *In Modelling and Simulation for Autonomous Systems (MESAS 2017)* (2017).

16. Lee, T. e. a. Geometric tracking control of a quadrotor uav on se(3). In *IEEE Conference on Decision and Control (CDC)* (2010).

17. T.Baca, G. M., D.Hert & V.Kumar. Model predictive trajectory tracking and collision avoidance for reliable outdoor deployment of unmanned aerial vehicles. In *nternational Conference on Intelligent Robots and Systems (IROS)* (2018).

18. Kruijff-Korbayová, I. *et al.* Tradr project: Long-term human-robot teaming for robot assisted disaster response. *KI-Künstliche Intelligenz* **29**, 193–201 (2015).