Multi-UAV-based stereo vision system without GPS for ground obstacle mapping to assist path planning of UGV

Jin Hyo Kim, Ji-Wook Kwon and Jiwon Seo

A multi-unmanned aerial vehicle (UAV)-based stereo vision system is proposed to assist global path planning of an unmanned ground vehicle (UGV) even in GPS-denied environments. The proposed system can optimally generate the depth map of ground objects and robustly detect obstacles. The proposed multi-UAV-based system with a movable baseline overcomes the limitations of a single-UAV-based stereo vision system with a fixed baseline. Thus, the performance of the proposed system does not degrade significantly based on the altitude of UAVs. The relative position and altitude estimation, multi-agent formation control and image processing techniques are considered to implement a prototype system. The experimental results demonstrate the performance of the implemented system for various baseline conditions between UAVs.

Introduction: Unmanned ground vehicles (UGVs) can be utilised in numerous applications including search and rescue missions and military operations. UGVs are normally equipped with various sensors such as RADARs, LIDARs and vision cameras for obstacle detection and avoidance. However, these sensors have the line-of-sight limitation and cannot perceive objects behind obstacles. Thus, they may not provide enough information for the optimal global path planning of the UGVs.

To overcome this limitation, a UGV may utilise additional information provided by unmanned aerial vehicles (UAVs), which have much longer and wider perception ranges [1, 2]. Garzon *et al.* [2] proposed an aerial-ground collaborative robotic system for obstacle mapping. Since the aerial images were obtained from a single camera on an UAV, a colour marker with zero height on the ground, for example, which is apparently not an obstacle, may be detected as an 'obstacle' in this approach. This problem can be resolved by an aerial depth camera that provides the height information of the obstacles as well as the location information. In literature, Stefanik *et al.* [3] suggested a single-UAV-based stereo vision system for terrain mapping, however, the obstacle detection capability decreases as the altitude of the UAV increases, because the stereo vision cameras have a fixed baseline which can be much shorter than the UAV's altitude.

This Letter proposes a multi-UAV-based stereo vision system for mapping ground obstacles to assist a UGV's global path planning. The operational concept of this system is presented in Fig. 1. Each UAV is equipped with a single camera, and the stereo vision system is implemented by two UAVs with a movable baseline. The detection capability of this proposed system does not degrade significantly in relation to the altitude of the UAVs because the baseline between the stereo vision cameras can be optimally adjusted. Furthermore, the proposed system is operational even under GPS-denied environments.

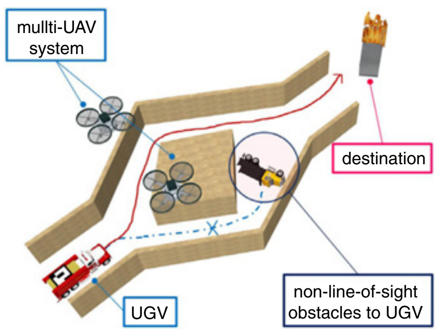

Fig. 1 *Operational concept of multi-UAV-based stereo vision system to assist UGV's global path planning*

The contributions of this Letter are as follows. A multi-UAV-based stereo vision system with a movable baseline is proposed to overcome the limitation of a single-UAV-based stereo vision system with a fixed baseline. The relative positions and orientations between the UAVs and UGV are obtained using a marker on the UGV. Thus, the system does not rely on GPS. Finally, the proposed system is implemented in a controlled laboratory environment with a motion capture facility, and its performance is demonstrated.

Multi-UAV-based stereo vision system: The proposed multi-UAV and UGV cooperative system is designed to operate even under GPS-denied situations. When GPS is available, the positions of the UAVs and UGV are readily obtained, and the multi-UAV-based stereo vision system can be implemented in a similar way to the regular stereo vision system with a fixed baseline between two cameras. However, the vulnerabilities of GPS draw significant attention [4], and the cooperative system without the dependency on GPS is much more desirable in numerous practical situations. For example, intentional GPS jamming should always be assumed for military operations.

A marker on the UGV is utilised instead of GPS to obtain the relative positions and orientations between the UAVs and UGV. The coordinate frames of the cooperative system are depicted in Fig. 2. UAV 1 and UAV 2 recognise the marker simultaneously, and the recognised images from the experiment are presented in Fig. 3.

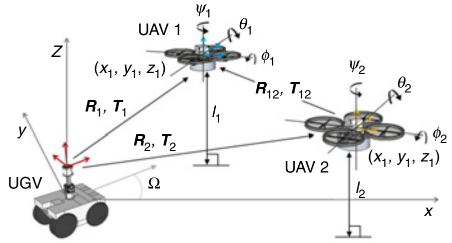

Fig. 2 *Coordinate frames of multi-UAV and UGV cooperative systems*

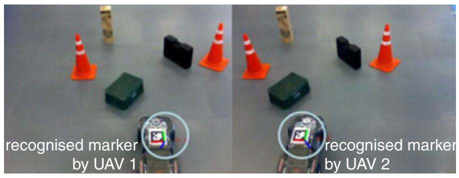

Fig. 3 *Marker recognition using camera of UAV 1 and camera of UAV 2*

Based on the recognised marker, the roll, pitch and yaw angles of UAV 1 and UAV 2 and the translation matrices $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$ can be calculated if the characteristics of the marker are already known as in the case of the proposed system. Once the roll, pitch and yaw angles are calculated, the rotation matrices $\boldsymbol{R}_1$ and $\boldsymbol{R}_2$ between the coordinate frames in Fig. 2 are obtained using (1)

$$\boldsymbol{R}_1 = R_z(\psi_1)\, R_y(\theta_1) R_x(\phi_1), \quad \boldsymbol{R}_2 = R_z(\psi_2)\, R_y(\theta_2)_x(\phi_2) \tag{1}$$

After obtaining $\boldsymbol{R}_1$ and $\boldsymbol{R}_2$, the rotation matrix $\boldsymbol{R}_{12}$ is given by (2). The translation matrix $\boldsymbol{T}_{12}$ is given by (3)

$$\boldsymbol{R}_{12} = \boldsymbol{R}_2(\boldsymbol{R}_1)^{\mathrm{T}} \tag{2}$$

$$\boldsymbol{T}_{12} = \boldsymbol{T}_2 - \boldsymbol{R}_{12}\boldsymbol{T}_1 \tag{3}$$

Thus, the relative positions and orientations between the UAVs and UGV are now available because the rotation matrices and the translation matrices contain all of the necessary information to calculate the relative positions and orientations between the coordinate frames attached to the UAVs and UGV.

Note that the marker should always remain inside the images from both UAVs during the operation, and the overlapped area of both images should be maximised to maximise the perception area of the multi-UAV-based stereo vision system. To maximise the overlapped area, the UAVs are controlled to contain the marker at the centre of the images. At the same time, the UAVs are controlled to maintain the given movable baseline between two cameras.

Experimental setup and results: To evaluate the performance of the proposed system, experiments are performed in a controlled laboratory environment with a real-time 3D motion capture facility, as shown in Fig. 4. The motion capture system provides precise real-time 3D positions of the reflective markers attached to the UAVs, UGV and all obstacles in the laboratory, with a millimetre-level accuracy. However, the multi-UAV-based stereo vision system operates without the position information from the motion capture system. The 3D positions are used only as the ground truth for the experiments. In the experiments, the UAVs are operated at an altitude of 2.7 m, and each camera with a 573 pixel focal length provides 640 × 480 imagery.

Fig. 4 *Experimental setup in real-time 3D motion capture laboratory*

To generate a depth map of obstacles, the intrinsic parameters of each camera are obtained using a conventional 10 × 7 chess board. The raw images from the cameras can be undistorted by adapting the intrinsic parameters and the $\boldsymbol{R}_{12}$ and $\boldsymbol{T}_{12}$ matrices from the previous section. Then, the stereo correspondence computation and the extraction of region of interests are performed. An example result of this processing is given in Fig. 5. Based on the processed images from two UAVs, a depth map of all objects can be obtained and the obstacles can be detected as in Fig. 6. Each recognised obstacle is indicated by a bounding rectangle.

Fig. 5 *Processing result for depth map generation*

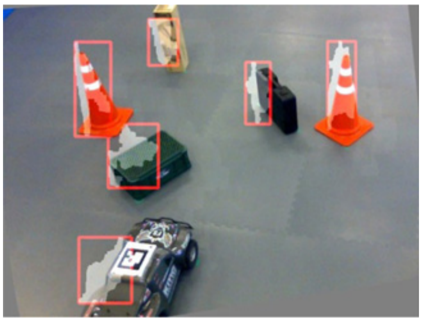

Fig. 6 *Detected obstacles by multi-UAV-based stereo vision system (baseline: 2132 mm)*

Similar experiments are performed with various baselines between two UAVs to demonstrate the performance of the proposed aerial stereo vision system under the movable baseline conditions. Table 1 presents the obstacle detection capability of the proposed system depending on baselines (the altitude of the UAVs is fixed to 2.7 m.) The longest baseline of 2132 mm provides the best detection capability as expected. All six obstacles are properly detected without any false alarms or missed detection in this case. Although the detection capabilities of other baselines are not as optimal under the given altitude, it is demonstrated that the proposed aerial stereo vision system is operational with movable baselines. Thus, the baseline can be adjusted to an optimal value depending on the altitude of the UAVs. For example, if the altitude is 305 m and the desired spatial accuracy of an obstacle is 1 m, the baseline needs to be larger than about 162 m under the same camera settings as used in this experiment (this value is calculated by (1) of [3].) Note that the baseline cannot be arbitrarily large because the aerial images from the UAVs may not overlap if the baseline is too large.

Table 1: Demonstrated performance according to various baseline conditions

Movable baseline (mm)	Detected obstacles out of 6	False alarm	Missed detection
124	6	3	0
247	6	4	0
374	5	1	1
884	6	3	0
1107	6	5	0
1404	6	1	0
2132	6	0	0

Conclusion: Aerial images can assist optimal path planning of a UGV, and the depth map of ground objects can provide further information for robust obstacle detection. A multi-UAV-based stereo vision system was proposed to optimally generate the depth map and to detect obstacles using its movable baseline. The proposed system was operational even under GPS-denied environments. The key implementation techniques for the proposed system included relative position and altitude estimation, multi-agent formation control and image processing for the depth map generation. The performance of the proposed system was demonstrated by the experiments with various baseline conditions in a controlled laboratory environment.

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One or more of the Figures in this Letter are available in colour online.

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References

1 Kim, J.H., Bae, I., Quan, C.H., Lee, S.H., Son, P.W., Rhee, J.H., Kim, S., and Seo, J.: 'Collaborative navigation of UAV and UGV using vision and LIDAR sensors'. Proc. of the Institute of Navigation 2013 Pacific PNT Meeting, Honolulu, HI, USA, April 2013, pp. 762–768
2 Garzon, M., Valente, J., Zapata, D., and Barrientos, A.: 'An aerial-ground robotic system for navigation and obstacle mapping in large outdoor areas', *Sensors*, 2013, **13**, (1), pp. 1247–1267
3 Stefanik, K.V., Gassaway, J.C., Kochersberger, K., and Abbott, A.L.: 'UAV-based stereo vision for rapid aerial terrain mapping', *GISci. Remote Sens.*, 2011, **48**, (1), pp. 24–49
4 Curry, C.: 'SENTINEL Project – Report on GNSS Vulnerabilities' (Chronos Technology, Ltd., Lydbrook, UK, 2014)