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Small and low-cost navigation system for UAV-based emergency disaster response applications

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ABSTRACT

Emergency disaster response and analysis rely on the timely availability of data acquired from the event site. Traditionally acquisition of such data requires the dispatch of ground personnel to the scene which however is often either inaccessible or dangerous. In the past few years, unmanned aerial vehicles (UAVs) have found more and more uses in environmental monitoring, pipeline inspection, search and rescue, and disaster assessment etc. UAVs can fly at a lower elevation and slower speed than manned systems which allows them to capture data with higher resolution, and they can operate in adverse weather and dangerous environments and acquire data autonomously, making UAVs an optimal platform for rapid-response applications.

Continuously available precise location information of the unmanned system by means of measurements from satellite and inertial navigation systems and other enabling sensors is advantageous. For small UAVs which dominate civilian applications including disaster and emergency management, the navigation system must be small size, light-weight, and low-cost due to UAV space, payload and cost constraints. Further, precise satellite positioning without ground base station is preferred for emergency response applications in order to reduce the operational cost and complexity in the field. These challenges are driven to the design of a small size, light-weight, and low-cost navigation system through integration of the latest satellite and inertial navigation technologies. The development of a small low-cost UAV and its navigation system as well as fly tests with respect to emergency disaster response applications are described.

I. INTRODUCTION

Emergency disaster response and analysis rely on timely availability of data acquired from the event site. Traditionally acquisition of such data requires the dispatch of ground personnel to the scene which however is often either inaccessible or dangerous. On the one hand, at the event of disasters, the dangerous situation makes it hard for responders to enter the site to safely operate the rescue mission and disaster assessment. On the other hand, time efficiency is critical for those missions, which leads to high pressure on the rescuers and operators. Although satellite and aerial remote sensing can cover a vast monitoring area these data are not always available and as a result detection is limited to the spectral sensitivity. Satellite and airborne remote sensing data are considered uneconomical in cost and time, especially when such data are required within a range of time frame like applications for hazard monitoring.

In the past few years, unmanned aerial vehicles (UAVs) have found more and more uses in environmental monitoring, pipeline inspection, search and rescue, and disaster assessment etc. UAVs can fly at a lower elevation and slower speed than manned systems which allows them to capture data with higher resolution. They can operate in adverse weather and dangerous environments and acquire data autonomously, making UAVs an optimal platform for rapid-response applications (Erdelj and Natalizio, 2016). For earthquake disaster events, Nedjati et al. (2016) have developed a medium-scale UAV helicopter system for commodity transportation in first respond place and Dominici et al. (2017) presented a post-earthquake case study on applying UAV photogrammetry. As is known, the high-resolution images are very useful to quickly detect the areas and structures that have suffered the worst damages, such as early damage assessment. A multi-UAV technology has been implemented and tested in a nuclear leakage disaster to detect and evaluate the nuclear radiation in Japan (Han et al., 2013). The radiation data were collected using MiniRad-V radiation sensor and displayed in real-time. UAV system could be used to apply various onboard sensors to acquire necessary data in the field, such as cameras and lasers. As UAVs provide appropriate platforms for high-resolution remote sensing, its applications in the geomatics field became increasingly common, facilitating the development of inspection and monitoring systems. Data processing systems are currently in development to make this technology a viable operational standard

(Dieter, et. al., 2005). For example, Assilzadeh et. al. (2010) evaluated damages caused by Hurricane Katrina in 2010, using satellite radar image processing while, at the same year, UAV was successfully applied for imagery data acquisition in order to assess the damage caused by the same hurricane (Adams et al. 2010; Adams and Friedland, 2011). The detailed information of the hurricane condition was collected with higher resolution data and without human involvement. Considering and comparing this methodology with traditional assessment methodologies include ground surveys that have innate limitations caused by timeliness and breadth in addition to site access that can be compromised, using UAV is an effective solution.

The main advantage of UAVs comparing to conventional satellite and airborne remote sensing systems is their low cost and applicability of usage in many weather conditions and time frame which both traditional surveying and airborne/satellites could not cover. Although UAVs have been widely used in many applications many capabilities involving with UAV still have not been practiced and many issues are not studied. Some challenges have been listed by Erdelj and Natalizio (2016) that include UAV localization, creating and maintaining the relay network, data fusion and handover issues, UAV system sustainability.

While capability to fly for a longer time and handling weight of onboard equipment are important factors for applications of UAVs, precise location (position, velocity and attitude) of the unmanned systems is essential in order to navigate in adverse weather and dangerous environments and to enable precise spatial analysis of remotely acquired data necessary for disaster assessment and response actions as well as platform stabilization and control. For UAVs, the original and widely-used low-cost satellite navigation technology was single point positioning (SPP) with the accuracy of several metres. A UAV-based RTK system was implemented by Stempfhuber and Buchholz (2011) which requires a ground base receiver station and a 3-minute starting procedure for each flight. Lack of a stand-alone onboard navigation system could lead to a UAV operational safety problem in case the radio link is lost. The integration of multiple sensors was not available in their system. A recent effort was made by the industry to develop correction data services with a goal to enable low-power, precise positioning, cheaper, more compact and scalable GNSS modules with RTK functionalities. An assessment of different low-cost GNSS receivers has been conducted to evaluate their performance with respect to RTK precision, availability, continuity and time to first fix (Jackson et al., 2018). The work has shown that in most open sky areas, the positioning accuracy with a low-cost GNSS receiver would be better than 10 centimeters within 20 seconds, providing an enhanced positioning solution for UAVs. The modules and chipsets used include Swift PiksiMulti, V08C-RTK, Emlid Reach, u-blox NEO-M8P, Skytraq S2525F8-RTK, and Hemisphere Eclipse P307. For inertial navigation, microelectromechanical technology (MEMS) led to the availability and variety of small and low-cost MEMS inertial sensors (accelerometer, gyroscopes, magnetometer, and barometer) and further the development of high-rate dynamic navigation systems for UAVs. Application of MEMS technology in UAVs could reduce the equipment weight and cost using inertial systems. The advantages of MEMS sensors are their small size and low cost (Melnichenko, and Osadchy, 2015), while the high-rate output of sensors support better dynamic control.

This paper describes a recent research effort to the development of a small and low-cost UAV based navigation and remote sensing system for emergency disaster response applications in the Positioning and Mobile Information Systems (PMIS) laboratory at the University of Calgary. The system design from sensor selection to integration will be described as well as test data acquired from field flights for performance analysis with respect to emergency disaster response applications.

II. DESIGN AND IMPLEMENTATION OF A UAV-BASED HAZARD REMOTE SENSING SYSTEM

The major components of the UAV-based hazard remote sensing and response system comprise a UAV for remote sensing and a ground response system. The UAV was developed using commercially available off-the-shelf parts and materials consisting of a power module, navigation sensors, communication system and cameras connected to a Raspberry Pi as well as a remote controller (see Figure 1). The response system consists of a ground control station and workstations to support hazard data analysis. The overall system design and implementation are provided in Figure 2.

Although the system is piece-by-piece designed and sensor outputs are high-rate and accurate enough for UAV applications, the performances of navigation sensors still experienced interference by a set of environmental, systematic or man-made interferences: temperature, operating voltage, propeller vibration, and static electricity by touches. For instance, the onboard accelerometer sensor was found unable to properly work under the temperature below -5°C which would affect the performance of the current navigation system. For a test conducted on a frozen day, we had to use a heater to put around the sensor chip but it would cost much battery power.

Moreover, the flight requires four motors for the UAV to work with high electrical current, due to the fluctuating air resistance and uncertainty of operator commands as the voltage amplitude would vibrate irregularly anytime. The above will affect not only motors but also any electrical appliances onboard. This leads to an increase of navigation sensor errors. On the other hand, apart from the electricity, low internal sample rate of low-cost MEMS is not able to capture the high-frequency physical vibration very well. Considering that vibrations will degrade the sensor performances, dynamically-calibrated propellers are implemented to provide better flight stabilities while the sensors are connected to voltage regulators for a more stable electricity voltage.

A Pixhawk flight control system with quadcopter frame Tarot 650 was used which contains the main control board and basic sensors (magnetometer, IMU and GNSS module). To set up the UAV platform for the application in our work, a u-blox M8P GNSS receiver is equipped to provide RTK positioning function for UAV navigation. In addition, the UAV are equipped with a host computer, cameras, and transmitters. According to Figure 2, the system is designed to include mainly four parts: Navigation Sensors, Ground Receiving & Control Systems, Communication, Remote Sensing Systems, and Power Source Modules. For communication, there are four different radio links with the ground station to enable the UAV operator and analyzer to stay connected with the equipment on board. A remote controller is applied to control the UAV by the operator through a 2.4GHz digital link. The UAV is accessible to the Ground Control Station through an analog link and a digital link for different types of data transmission. Furthermore, an Internet connection via a 4G module is embedded for accessing GNSS base station data and PPP correction data or any data needed by the processing center. Most importantly, the remote sensing systems collect essential imaginary data and perform data analysis for the disaster and send warnings to the Ground Control Station through a digital radio link. The cameras and computers are connected with the navigation functionalities through the main control board to provide high-rate accurate navigation information. Due to the fact that high-speed computing capabilities are needed for synchronized imaginary processing and data streaming, a Raspberry Pi 3 is used along with the main control board to perform UAV control and basic navigation functionalities.

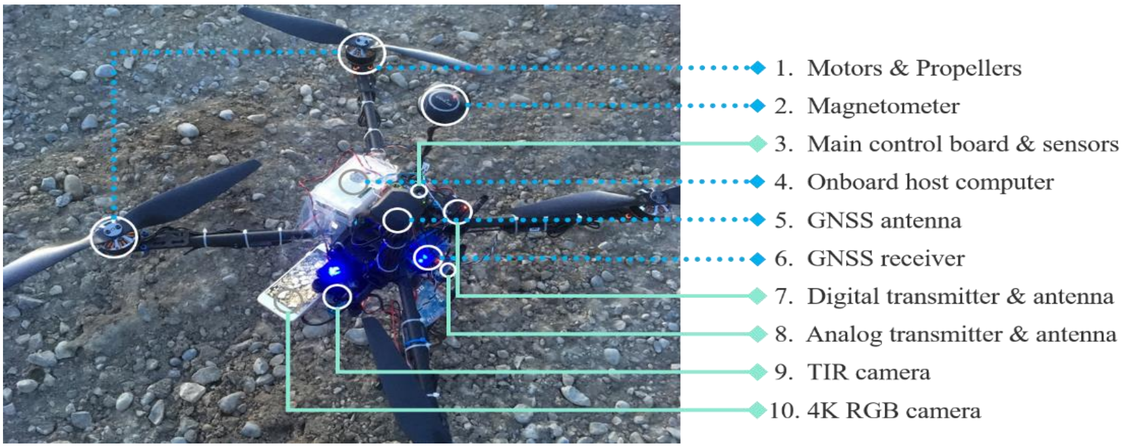


Figure 1: UAV Platform

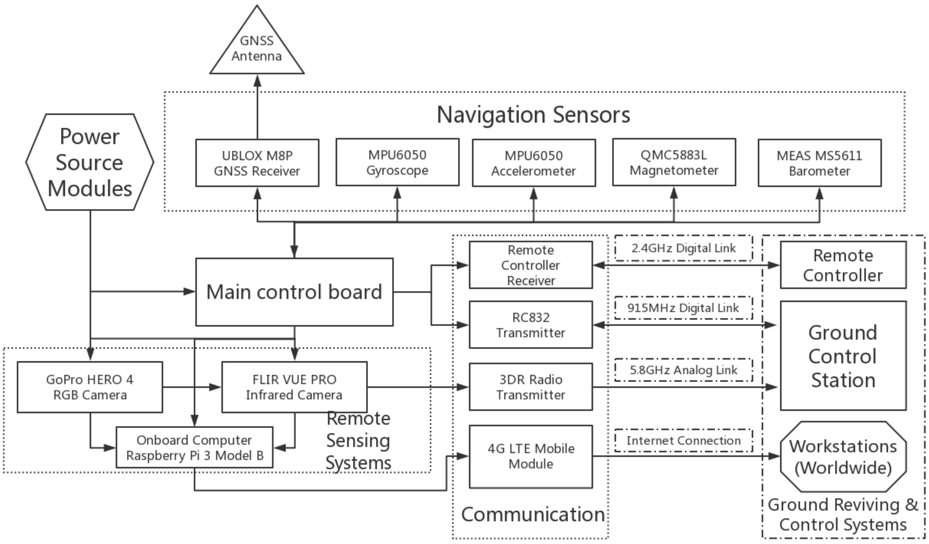


Figure 2: Overall system design and implementation

III. A Small and Low-cost Navigation System

An effort has been made to design a small size, light weight, and low-cost navigation system through integration of the latest satellite and inertial navigation technologies. This is based on an integration of precise point positioning (PPP) and MEMS-based inertial systems. PPP is advantageous since it does not require ground base receiver stations so there will be no limitation of baseline length and a continuous radio link to the base receiver station as the case in RTK. Different from SPP, the obtainable positioning accuracy of PPP will be at decimeter to centimeter level with small and low-cost satellite and inertial sensors. Through integration of satellite navigation with inertial navigation technologies (barometer, accelerometer, gyroscope, and magnetometer), the developed navigation system is able to provide enhanced availability and continuity of precise navigation solutions, especially in challenging environments.

A precise point positioning model based on un-combined observations (UPPP) is adopted (Li et.al. 2013). The satellite orbit and clock errors are corrected using precise GNSS products available from the National Centre for Space Studies (CNES). For tropospheric effect, the zenith hydrostatic delay (ZHD) could be obtained precisely using the Saastamoinen model assisted with GPT meteorological model and GMF projection function (Li et al. 2013) while a first-order Gauss-Markov random model is applied to model and estimate the zenith wet delay (ZWD). When with a low-cost single-frequency GNSS receiver, a first-order Gauss-Markov random model is applied to model and estimate the residual ionospheric effect, tightly constrained with real-time ionospheric product available from CNES (Nie et al. 2019). For other remaining error sources, the solid and ocean tide corrections are calculated based on methods provided by IERS (Petit and Luzum 2010). The CODE’s 30-day DCB product is used to mitigate the bias effects.

To ensure continuous high rate navigation solutions, a loosely coupled integration of MEMS IMU and PPP is applied. The PPP engine continuously computes GNSS position as the input to the integration Kalman filter and IMU data continuously repeat mechanization after sensor biases have been corrected. The position, velocity, and attitude from the mechanization are used as input for the integration filter to integrate with GNSS position. After the integration filter, the calculated sensor bias feedback updates the sensor bias in the IMU mechanization. In this paper, the estimated parameters by the integration Kalman filter are the position, velocity, attitude, accelerometer bias, gyroscope bias. The sensor calibration is conducted using the six-position method before the UAV takes off.

IV. Navigation system test and analysis

Field fly tests have been conducted using the developed quadcopter UAV with 650mm frame size. As it is shown in Figure 2, a Raspberry Pi 3 is used as the onboard host computer. A u-blox M8P single frequency GNSS receiver with RTK function is installed onboard to provide the raw GNSS observation to the host computer. The RTK engine of M8P can provide 0.025m+1ppm CEP so its RTK solutions are therefore used as the ground truth for all the tests performed. A 3DR digital transmitter connected with the host computer is used to transmit the correction data needed by the PPP engine running on the host computer. Since u-blox M8P does not support the Galileo constellation and the availability of BeiDou satellites is still compromising, the flight tests were conducted in a GPS+GLONASS mode. In order to ensure that PPP solutions have achieved a status of convergence, the navigation system is started 30 minutes before the UAV take-off.

The fly test was conducted in an area that is mostly open sky except for the north direction, which is covered by a forest of about 6m tall. The UAV approached the forest edge at about the epoch 00:24:30, 100 seconds after take-off. The trajectory of this test could be seen in Figure 3 (Map data: Google, DigitalGlobe) in which the yellow color points are float solutions of M8P and the green points are fix solutions. The overall RTK fix rate is 76.3% and it is still reliable to serve as the reference most of the time. The UAV took off at about epoch 00:22:50 and landed at about the epoch 00:30:00. The flying test lasts about 400 seconds.

Figure 3: UAV test trajectory

Figure 4 shows the PPP positioning errors since the power on of the navigation system while the last 400 seconds are the UAV flight period. It could be seen that PPP reaches convergence within 1000 seconds horizontally and 1400 seconds for the up direction. Figure 4 also demonstrates that after taking off the positioning error becomes larger, especially in the up direction. This is considered to be caused by the vibration of the UAV. Although there is a positioning dynamic model (set as 2g in this test) inside the u-blox M8P RTK engine, there is no such constraint in the PPP engine. So, in this way, the output of M8P RTK would look smoother but the PPP would show the impact of the real vibration dynamics of the GNSS antenna mounted on the UAV with a carbon filter bar.

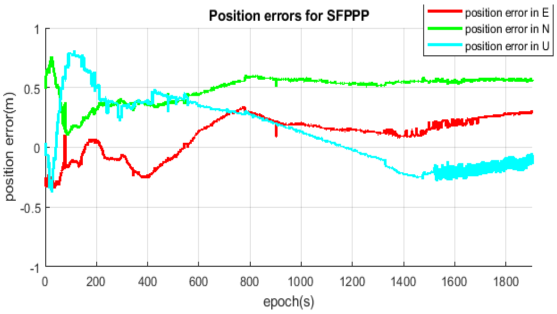


Figure 4: Single frequency PPP position errors

To further assess the performance of the on-board PPP during flight, the PPP alone positioning result during flight time is shown in Figure 5. It indicates a good position precision better than 15cm STD in the horizontal direction and 24cm STD in the vertical direction. It is also noted that there is a systematic bias in all three directions. This is because the CNES ionosphere product employs a resolution of 6 spherical harmonics degrees and 6 spherical harmonics orders, which may not work well worldwide. As a result, it could cause a bias in the coordinate estimates. A better RMS result could be expected with a more accurate ionosphere correction product. It could also be noticed that there are some minor coordinate jumps in the east direction from the beginning to 200 seconds. This is caused by unstable RTK ambiguity fix over the first few minutes after taking off. It could be seen that, during the flight period near the forest, the PPP still provides very good solution as there are many satellites visible from the south/east/west direction in an open-sky environment. This reveals that PPP can output reliable positioning under certain moderate GNSS-denied environments and the reliability can be enhanced when PPP is integrated with IMU.

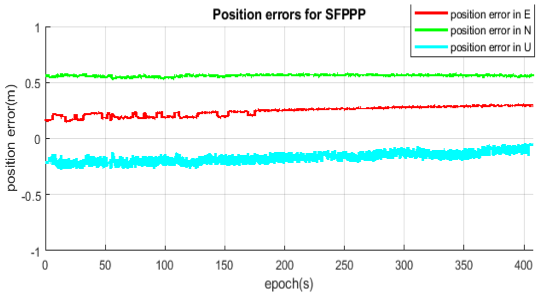


Figure 5: Single frequency PPP position errors after UAV take-off

Table 1: Positioning accuracy statistics

Direction	STD (m)	RMS (m)	Bias (m)
East	0.045	0.244	0.240
North	0.009	0.561	0.561
Up	0.049	0.177	-0.170

Figure 6 and Tab. 2 show the integrated PPP/IMU positioning error, which reveals a similar accuracy level as the PPP solutions. No improvement could be seen in this integrated solution. Even some minor jumps could be seen as well in the three coordinate directions. Due to the great difficulty of error modeling of dollar-level MEMS IMU sensor, more efforts are needed for the fusion algorithms. It could also be seen from Figure 4 that the position reach to convergence within 50 seconds after estimated IMU sensor biases reach convergence during this short time period. Although no improvement on overall positioning precision could be seen, the results are expected to improve with better fusion algorithms than the presented initial tests. In addition to precision, the availability of position output rate at 250 Hz (as the IMU outputs for 250 Hz) will bring benefits to applications, which is quite vital for UAV to fly in high dynamics environments.

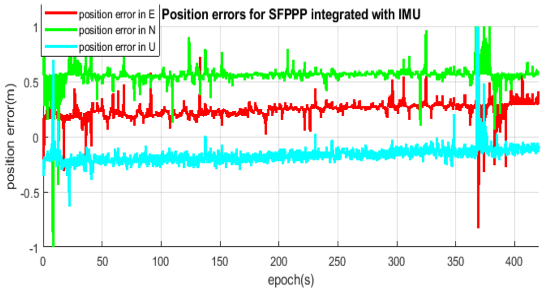


Figure 6: Single frequency PPP integrated with IMU position errors

Table 2: Positioning accuracy statistics

Direction	STD (m)	RMS (m)	Bias (m)
East	0.108	0.263	0.240
North	0.160	0.579	0.556
Up	0.085	0.185	-0.164

It is worth noting that there is a significant position jump at about epoch 370 seconds, Figure 5 shows the IMU data time interval over the testing period. It could be seen that at epoch 370 there were some serious data loss events, which made the integration filter hard to predict the navigation parameters over this data lost period, especially for a UAV flying in highly dynamic applications.

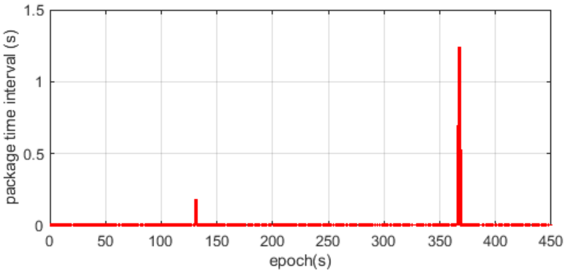


Figure 7: IMU package interval

To sum up, the flight tests indicate that the PPP alone solution provides very good positioning precision at centimeter to decimeter level accuracy. The integrated PPP/IMU didn't show improvement in positioning accuracy which requires further improvement of sensor fusion algorithms. The integrated system can extend the low-rate GNSS positioning solution into high-rate integrated positioning solution up to 250 Hz, which is vital for high dynamics applications for better UAV control.

V. UAV-BASED HAZARDS DETECTION TEST AND ANALYSIS

A mini UAV equipped with RGB and Infrared cameras for the data acquisition and a real-time data communication system are key components in the development of application systems for disaster management. This was considered in the design of the developed UAV described and tested in this work. Depend on applications, the imaging sensors must work in an appropriate range of electromagnetic wavelength and resolution. Two cameras in RGB and IR band are used to take digital photos or analog videos for situational analysis, detecting, monitoring, forecasting and hazard management. Data can either be saved on SD cards inside the cameras or transacted from the UAV to a local computer through digital or analog transmitters. A program has been developed in Python to read the data from the camera driver connected to the main computer onboard the UAV and transact in real time to the server on the ground workstation through the Internet network for further analysis, processing, and assessment. In the following application, a flight conducted to test the hazard detection and monitoring over a river bank is conducted.

A. *Description of hazards*

First, the hazard concepts and the features of hazards that developed UAV could support are described. The term "hazard" normally refers to all atmospheric, hydrologic, geologic, anthropological activities and wildfire phenomena that have the potential to affect humans, their assets, or their activities adversely (Burton et al. 1978) and hazard management refers to all activities in before, during and after, to reduce those impact from a hazard event. Identifying historical risk assessment, finding a hazard-prone area, planning for prevention and facilitating required elements for reducing lost in case hazards happen again are the example of pre-hazard managing activities. During hazard, event management refers to activities like monitoring, early warning, modeling for hazard and search and rescue of peoples or lives that affected by hazards. Damage assessment, reconstruction, and planning for the future possibility of hazards would be the major activities after hazards occur.

Among natural and anthropological hazards, forest fire, flood, avalanches, extreme cold, tornado, pipeline accidents, and oil spills are common in Alberta. The developed UAV equipped with an inferred camera could help minimize damages and hazard management as well as search and rescue as described in the following:

- At the event of a forest fire the inferred camera can help identify hotspots, fire locations, and modeling for risk assessment and emergency response.
- At the event of a flood as IR is too sensitive to a water body, the UAV could help for monitoring water extent and inundated area, or measuring river width to model early warning, risk assessment, and forecasting.
- At the event of avalanches, it could help for monitoring risk area.
- At the event of a tornado, since normally access through the air is too difficult and dangerous for helicopters, but UAV based GNSS/MEMS technology support stable flight and low-cost damage assessment, situational analysis and search and rescue mission process.
- At the event of pipeline accidents and oil spills the best sensor for detecting and monitoring leakage and outflow for UAV based systems is IR camera. IR image is too sensitive to oil spills on the ground and water body environments. The UAV system can be used for monitoring, trajectory modeling, and cleanup planning.

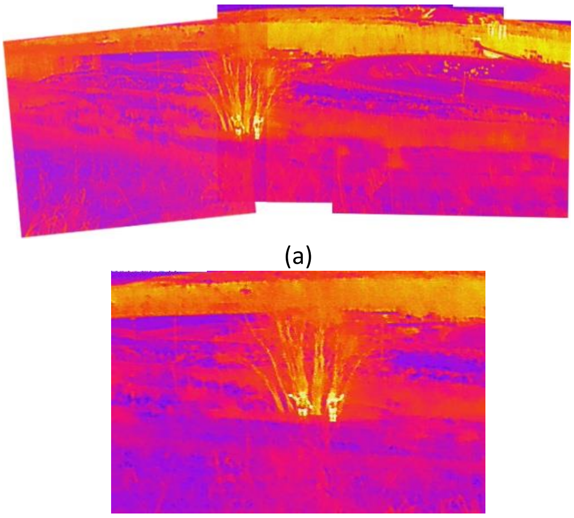
B. *IR camera Image Processing*

The IR and optical cameras onboard the UAV could help manage anthropological and natural hazard in the various stages. The IR camera specifically is used for night time to distinguish objects and help for situational analysis at the event of hazards.

Thermographic or infrared cameras are usually used to detect radiation and determine the gradient of temperature. During night or absence of the sunlight, living objects are detectable by these camera images (Figure 7) because the temperature of living bodies is higher than the surrounding environment.

Using PPP/MEMS IMU based UAV system helps generate precisely georeferenced images so that all locations are registered with X and Y direction and enable mosaicking number of images for better situational analysis and search and rescue missions at the event of hazards especially during night time. The IR camera onboard the UAV was used during a flight test to outline the Elbow River and the river bank to examine the capability of the UAV system.

The Elbow River is a river in southern Alberta, Canada which flows from the Canadian Rockies to the City of Calgary. The river suffered a heavy rainfall on in 2013 that triggered catastrophic and worst flooding in Alberta's history. Areas along the Elbow River closed to the city were particularly affected and the vicinity of the river was placed under a mandatory evacuation order as the river spilled over their banks and flooded communities which were the largest evacuation order in the city's history. This catastrophic event reviles the necessity of monitoring and study on this river to define vulnerability of the locations along the riverbank as well as flood possibility. Monitoring river width can be used as a model for flood forecasting.


(a)

(b)

Figure 7: UAV flight and images by IR camera during night time (a): Mosaicking several images (b): Image after radiometric correction detecting human bodies and the detailed surrounding area.

Figure 8 (a) presents the IR image taken from a flight test with the developed UAV over the Elbow River in the Calgary area. The picture was taken after sunset (at around 8:00 pm local time) in absence of the sunlight. The thermal wavelength at spectral band 7.5 - 13.5 µm is sensitive to liquid water, ice and snow as well as the gradient of their temperature.

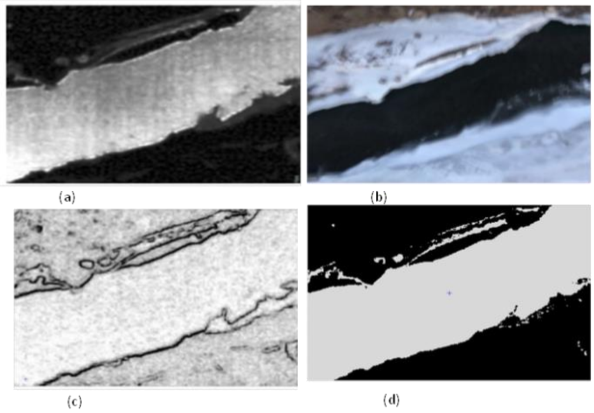


Figure 8: (a) Original IR image from FLIR Vue Pro in spectral band 7.5 - 13.5 µm; (b): RGB optical image from 4K RGB camera; (c): Texture analysis of the IR image to delineates water body and land features; (d): Extracted water body using ISODATA Unsupervised clustering module.

Figure 8 (b) shows the RGB image taken from the 4K RGB camera lunched over the UAV. As it displays the ice and water body cannot be distinguished by RGB image even during day time, so the water edge in this image is not clear. Figure 8 (c) is the result of the texture analysis and Figure 8 (d) is a classification of some composite channels which can rectify water edges clearly.

Segmentation of the composite channels (Figure 9) was used to delineate the river and surrounding area. Different feature of the water, ice and snow area were recognized along the river bank. It was the results verified with data taken during the day time at the same location.

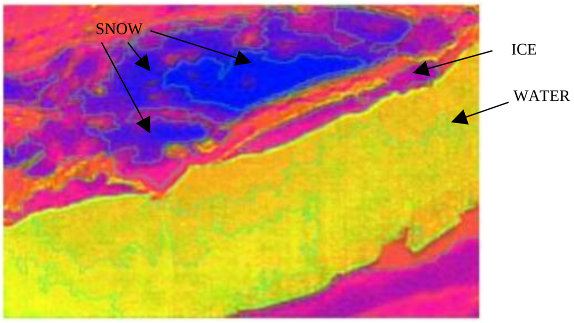


Figure 9: Image segmentation represents different water, ice, snow conditions along the Elbow River

VI. CONCLUSIONS

This paper described the development of a small size and low-cost navigation system for UAV-based emergency disaster response applications. Since traditionally acquisition of such data requires the dispatch of ground personnel to the scene which however is often either inaccessible or dangerous, UAVs offer an effective alternative for environmental monitoring, pipeline inspection, search and rescue, and disaster assessment etc. The navigation system development is based on an integration of low-cost satellite and inertial navigation sensors (low-cost GNSS chips and MEMS-based IMU) to provide continuously available precise location information of the unmanned system. Since precise satellite positioning without ground base station is preferred for emergency response applications in order to reduce the operational cost and complexity in the field, precise point positioning is employed. The system design from sensor selection to integration has been described and flight test data from the UAV was analyzed to demonstrate positioning accuracy of the navigation system and applications to emergency disaster response applications. The UAV flight tests results and analysis, however, are preliminary at this stage which requires further algorithm improvements for both PPP and PPP/MEMS IMU data fusion components. This work is currently underway.

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