THE CLOSE-SEARCH PROJECT: UAV-BASED SEARCH OPERATIONS USING THERMAL IMAGING AND EGNOS-SOL NAVIGATION

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GeoInformation for Disaster Management 2011, Antalya, Turkey

KEY WORDS: UAVs, SAR, EGNOS, Thermal imaging, geomatics

ABSTRACT:

This paper will introduce and describe the goals, concept and overall approach of the European CLOSE-SEARCH project. CLOSE-SEARCH stands for ‘*Accurate and safe EGNOS-SoL Navigation for UAV-based low-cost SAR operations*’ and is being conducted by a consortium that brings together technologists, scientists, 3D spatial data providers and a search-and-rescue (SAR) end-user to guarantee both technology and market push influence. The goal of CLOSE-SEARCH is to integrate in a small Unmanned Aircraft (UA), a thermal imaging sensor and a multi-sensor navigation system (based on the use of a Barometric Altimeter (BA), a Magnetometer (MAGN), a Redundant Inertial Navigation System (RINS) and an SBAS-enabled GNSS receiver) with an Autonomous Integrity Monitoring (AIM) capability to support the search component of SAR operations. The proposed integration will result in a Hardware and Software prototype that will demonstrate an end-to-end functionality. For reasons of maneuverability the proposed UA will be a helicopter. In addition, it is also the goal of CLOSE-SEARCH to demonstrate the added value of a future multi-constellation augmented GNSS configuration, like Galileo/GPS-EGNOS or Galileo/GPS-SoL.

The context of CLOSE-SEARCH is that of SAR operations in a number of critical circumstances: outdoor sports, natural/man-made disasters... and covers a broad range of situations: from position-tagged –georeferenced– distress calls, to loosely-georeferenced and non-georeferenced ones. The proposed search system can be operated day and night in rather inaccessible areas. By systematically flying over a region and through the detection of the body heat, CLOSE-SEARCH is intended to identify disaster survivors or lost people. In other words, CLOSE-SEACH would be a low-cost and robust system to support the SAR search component in situations of just approximate knowledge of the search geographic area.

1. INTRODUCTION

1.1 Unmanned Aircrafts in Search and Rescue missions

The use of UAVs for SAR operations is not new –the application is even mentioned in the English version of the Wikipedia. When a small plane crashes in a remote area, or a fishing boat is lost at sea, or a hurricane devastates a region, or simply a person gets lost while he/she was hiking, SAR teams must scramble every available resource to scan vast areas for evidence of victims or wreckage. For this purpose, UAs equipped with thermal sensors can be programmed to fly predefined search patterns at low altitudes –from 30 m to 150 m-, transmitting real-time imagery back to a command and control station via a data link. For example, Unmanned Aircrafts (UAs) used in the Iraq and Afghanistan wars were deployed to find people trapped in New Orleans’ buildings devastated by Hurricane Katrina’s flood waters. These UAs were equipped with thermal imaging systems to detect the body heat of storm survivors.

Generally speaking, Wilderness Search and Rescue (WiSAR) entails searching over large regions in often rugged remote areas. Because of the potentially limited mobility of ground searchers, WiSAR is an ideal application where small or tactical UAVs have been used to provide aerial imagery of the search region. Although less spread in Europe than in North America, it can be said, that the use of UAVs -more in general, Unmanned Aerial Systems (UAS) including the Control Station (CS) and Data Link (DL)- for WiSAR is evolving rapidly.

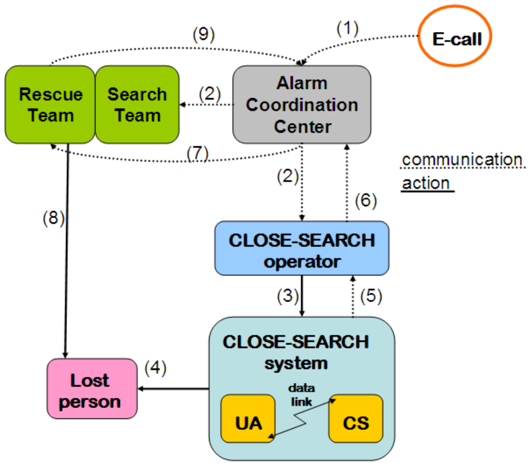

Figure 1: The CLOSE-SEARCH system within a Search-And-Rescue action chain

As CLOSE-SEARCH targets at the *search* missions, the proposed system shall be integrated in the SAR missions just as one more piece of the search mechanism. Figure 1 shows an action flow diagram of a SAR mission in which the CLOSE-SEARCH system would be framed. Given a situation where a person is lost (in one of the previously described contexts), this use case starts in (1), where an emergency call is received by the Alarm Coordination Center (ACC). The minimum input information that should be provided in that call is a loosely georeferenced area, called *incident zone*, estimated in view of the last time the person was seen or known to be and the potential mobility (as a function of the person's health and terrain morphology. This zone defines the search operation scenario. In (2), the ACC contacts the CLOSE-SEARCH operator as well as other search teams in order to specify the incident zone and thus trigger the search mission. Then, the CLOSE-SEARCH operator initiates the mission (3), by reaching the incident zone as close as possible, planning the flight and executing it. When the person is found (4), the CLOSE-SEARCH system sends the corresponding data (that is, the *georeference* of the lost person) to the CLOSE-SEARCH operator and the latter returns the communication back to the ACC (6) to provide the so-called *rescue area*, a 10m x 10m region on ground where the lost person dwells. With this information, the ACC can contact the rescue team (7) to proceed with the person rescue (8). Once the whole operation is closed, a final mission closure message is sent to the ACC (9).

1.2 Key application enablers and the CLOSE-SEARCH state-of-the-art contributions

As discussed, the use of UAS in SAR applications may still seem very restricted to major, seldom catastrophes, in which big efforts are deployed and the risk and consequences of loosing a UA (even causing an impact on ground) is minimized, analogously to the military applications. However, in order to spread this application closer to the public, mass-market level, where local civil protection authorities, small companies, sport clubs, etc. may benefit from it, the operation -i.e., navigation- of the UAs shall be safe. For this to happen, three main conditions shall be met:

1. the predefined search path shall be followed within given accuracy and integrity levels,
2. considering the relative low flying altitude, accurate and up-to-date geospatial databases (mainly for DSM information) shall be available and integrated with the UAS, and
3. a collision avoidance system shall be in place; the so-called Sense-and-Avoid (SAA) systems.

Regarding the identified key application enablers, CLOSE-SEARCH advances on the state-of-the-art for the above points 1 and 2. With respect to item 1, CLOSE-SEARCH will demonstrate safe navigation with aided GPS-EGNOS and the relevance of the future Galileo and modernized GPS-SoL services. Moreover, CLOSE-SEARCH will proof EGNOS-enabled INS/GNSS integration valid for UAV platform types by combining the former concept -i.e., EGNOS-enabled INS/GNSS integrated navigation- with the use of low-cost redundant IMU configurations, baro-altimeters and magnetometers. Finally, the integration takes advantage of the Autonomous Integrity Monitoring (AIM) implementation, which extends the traditional Receiver Autonomous Integrity Monitoring (RAIM) capabilities to *all* the navigation sensors integrated within the filter. We believe that this highly redundant configuration provides the level of precision, accuracy, and reliability needed for the navigation of an UAS/UA. CLOSE-SEARCH takes a new approach to UA safe navigation: the standard line of thought is that low-cost GPS/INS is not fit for the purpose of autonomous UA navigation and that, consequently, some sort of Simultaneous Localization and Mapping (SLAM) setup and algorithm are needed. SLAM relies on image matching and camera orientation techniques. However, in the context of WiSAR, the SLAM approach underestimates the possibilities of BA/RINS/GNSS and its own limitations (low texture images, operations in the darkness, operations at sea, repetitive patterns in images, etc.), and thus may not be sufficient or effective at all.

Further to this, and with respect to the item 2, CLOSE-SEARCH will demonstrate how 3D geospatial information -not only Digital Elevation Models (DEMs) but also and mainly DSMs- can and must be used in combination with navigation systems. Due to the temporal and funding limitations of the project notwithstanding, the proposed concept will demonstrate how 3D landscape models can be used to improve the search operations (identifying occlusions and other limitations of aerial imagery) and avoid collision with the terrain or other objects. CLOSE-SEARCH may generate useful feedback to geospatial data producers on the required level of detail (electrical power lines, communication towers, etc.) of their data bases.

Last but not least, we note that condition 3 shall not be interpreted as a barrier to the practical application of the proponed concept. Certainly, as mentioned earlier, the still unregulated integration of UAS/UAs into the civil regulated airspace is a major commercial market barrier to many applications of the UAS technology. However, the CLOSE-SEARCH application will not suffer from this as, in the circumstances of WiSAR, the use of the technology is rather sought than restricted and the proposed flying altitude is low.

1.3 EGNOS added value over existing solutions and integration approach

When tackling the navigational performance aspect, one shall ask how to achieve [the desired] accuracy and precision and how reliable is the solution obtained. Both questions [forcedly] push us to a review of the GNSS navigation techniques. So far, in GPS [and GNSS] navigation, accuracy is achieved with differential techniques; i.e., on the basis of measurements collected at well surveyed ground stations. The method can be more or less sophisticated, ranging from just one user established single station and simple error modelling -i.e., Differential GPS (DGPS)- to a multi-user regional/global network of stations and advanced error modelling including orbit and clock errors. EGNOS belongs to the last class. On the other side, similarly, a network of well surveyed ground stations constitutes the basis of integrity, as the incoming GNSS signals are continuously processed and their derived measurements compared against computed reference values. From an accuracy standpoint, EGNOS based navigation has advantages over the existing, commonly used solutions like *non-differential GNSS*, *private and publicly available DGPS and DGNSS*, and *user established RTK setups*.

Indeed, it would just too risky to fly predefined search patterns at low altitude (down to 10 meters above ground) with non-differential techniques. Nonetheless, WiSAR imposes its own constraints on positioning techniques. As an example, RTK solutions would be, for CLOSE-SEARCH, a waste of precision that, on the other side, require some time and constraints on the establishment of the well-surveyed reference point and supposes an eventually not-affordable communication link. Clearly, a regional/global continuous DGNSS service is the ideal solution for an application like CLOSE-SEARCH that has to respond to emergency situations with a go-and-fly action, anywhere and anytime. From an integrity monitoring standpoint, most local DGNSS and RTK solutions do not provide integrity figures and, therefore, are not amenable for CLOSE-SEARCH –integrity indeed deals with the avoidance of accidents caused by navigation signal faults, and this is of major importance for UAV-based missions as UAVs are on the eye of the storm.

With respect to the integration approach, the navigation solution of CLOSE-SEARCH will be computed in a least-squares approach, solved by Kalman filter or normal equation approach, where the IMUs will play the role of primary navigation sensors whose drifts will be removed by EGNOS-GNSS update measurements in a close-coupling INS/GNSS integration scheme. In other words, the INS mechanization differential equations will be numerically integrated and the result merged by least-squares with the EGNOS-healthy (integrity functionality) and EGNOS-corrected (accuracy functionality) pseudoranges. We note that, due to the high redundant navigation sensor configuration, the Autonomous Integrity Monitoring (AIM) function is feasible; that is, not just redundant pseudorange measurements like in standard Receiver Autonomous Integrity Monitoring (RAIM) techniques, but every sensor measurement used in the least-squares is monitored to check to eventually perform Fault Detection and Exclusion (FDE). Finally, classical system availability (computation of Protection Levels and checking against Alert Levels) will be performed and, in an advanced phase of the project, extended to the full time-position-velocity-attitude (tPVA) domain.

2. THE CLOSE-SEARCH SYSTEM

2.1 State of the technology in the CLOSE-SEARCH consortium and evolution during the project

The main components of the CLOSE-SEARCH system are the Navigation System (NS) of the Institute of Geomatics, the UAS (including the UA, the CS and the data link) of AIN, the thermal camera of AIN, the GNSS receiver simulator of DME, the redundant IMU (RIMU) system of EPFL and the 3D countrywide LiDAR-based DSM of the ICC.

The Institute of Geomatics NS is a real-time tPVA server. For the acquisition component, several sensors are integrated (JAVAD TR-G3T GNSS receiver with GPS L1, L2, L2C, L5, Galileo E1, E5A, GLONASS L1, L2, WAAS and EGNOS capability, a Leica magnetometer, a Honeywell Barometric Altimeter (BA), Northrop-Grumann LN-200 IMU) and for the processing component, the IG's NAVEGA real-time generic Kalman filter is used. AIN counts with three UAS/UA of the helicopter type, among which the UAR35 (Maximum Take-Off Weight (MTOW) is 75kg) is its contribution to CLOSE-SEARCH. The UAS/CS is an in-house development of AIN. The thermal camera (Raytheon 2000B) is sensitive in the 8-12 µm spectral range and is equipped with two lenses (25 mm f/1.0 and 100 mm f/1.0). DME contributes to CLOSE-SEARCH with the GRANADA GNSS receiver simulator in two versions: the GRANADA FCM Blockset (fast simulator) and the GRANADA Bit-True Simulator. The RIMU system of EPFL consists of four Xsens low-cost IMUs (three IMUs of the type MTx-i and one of the MTi-g type) and their acquisition SW.

2.2 Architectural overview of the whole system

Figure 2 shows the CLOSE-SEARCH system architecture. This architecture is twofold: the *air* and the *ground* segments.

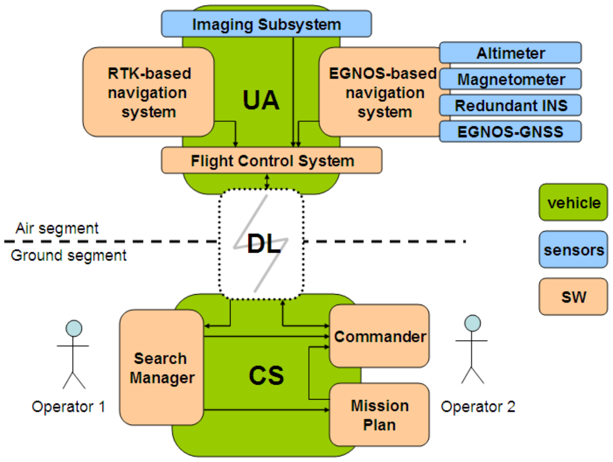

Figure 2: Architectural overview of the system

On the *air* segment, the UA is depicted including the EGNOS-based navigation system and the integrated sensors (left) and RTK-based navigation system, which is AIN's actual system (back-up in CLOSE-SEARCH, left). These two subsystems provide a navigation solution to the Flight Control System (FCS), which is in charge to perform the platform control and interact with the communication unit on-board. Another important piece on board is the Imaging Subsystem (IS), composed by the thermal camera, video encoders and Video Recorder (VR) to eventually store images on-board. An optical camera is also envisioned to provide completeness to the remote sensing subsystem.

On the *ground* segment, three main pieces are implemented: the Commander is the AIN's SW development to perform the command-and-control of the UA (monitoring the mission, managing the route,...); the Mission Plan is a genuine CLOSE-SEARCH work based on a GIS-platform to design the mission in terms of flying path, scanning patterns, image overlaps...; and finally, the Search Manager is a SW tool to interact with the IS outcome. It is very important that the user can visualize and [eventually] pin-point any object in the image to geo-reference it and input it to the mission information as a target candidate.

3. FIRST TEST CAMPAIGN

Due to its iterative-incremental nature, there are two defined test phases at the middle and end of the project. The first test campaign (scheduled for the second half of November, 2010) was devoted to test the mechanical, electrical and SW interfaces of the system and to demonstrate preliminary end-to-end capabilities. It is intended that, for the second test campaign (September 2011), a mature CLOSE-SEARCH prototype will be presented extensively fulfilling the user requirements and demonstrating advanced end-to-end functionalities. The first test campaign included laboratory and pre-field tests on controlled scenarios to verify and validate those system components needing a higher degree of validation within the project. The fact that previous R&D work has been brought together in the project inherently brings along different levels of maturity. For example, the AIN's UAS/UA and UAS/CS have been widely tested and thus require less validation effort. Finally, the first test campaign concluded on the so-called field test. The chosen scenario for the field tests was the town of Copons, Catalunya (figure 3). This location was suitable for many reasons: it is an easy accessible area but far away from big urban areas (nonetheless, local permissions were obtained) and different land features were present (smooth and rough terrain, vegetation...)

Figure 3: Unmanned Aircraft and Control Station on November, 25th -the first CLOSE-SEARCH test campaign

3.1 Description of the test flights

On November, 25th 2010 three flight tests were executed by the UA to test different features (figure 5). On the first flight, different height and speed profiles were executed and an active thermal target was used. Precisely, on one hand, the UA hovered at 10, 30 and 50 meters height above the thermal target. On the other hand, and maintaining a 50 meter height the UA flew in straight line over the target at 4, 6 and 8 meters per second. The intention of this test was to assess the optimal height and speed UA profiles in relation to the thermal target perception; that is, how high and fast should we fly in order to ensure recognition of targets in ground. In order to simplify target recognition, a 2m x 2m metal and polystyrene chess-type layer (figure 6) was used. Underneath the layer, a thermal blanket was used in order to create intense thermal emission and enable clear target recognition.

On the second and third flights, a strip-based scanning pattern was proposed at constant 4 m/s horizontal speed but different height profiles: 50 meters and 30 meters respectively. On both tests, several active/passive thermal targets of different nature were used and spread over a hectare. Besides two 2m x 2m metal and polystyrene layers, four persons dwelled on the area in different postures during the flights. One person stood, another person sit on ground beneath some low-height vegetation and finally two persons lied on the ground. Each target location was previously surveyed with precision GPS for *a posteriori* validation matters. The aim of these tests was to demonstrate end-to-end capabilities in search missions: with respect to the air segment, to demonstrate the capacity of flying and thermally scanning a given area, and to the ground segment, to control the mission both for the UA performance and for the IS subsystem.

For all flights, the 3D geospatial information extracted from LiDAR-based DSMs provided by ICC was used for planning the missions a priori (that is, not on site). UA waypoints and actions were derived from the three flight specifications.

3.2 Test results and preliminary conclusions

In general terms, the three tests were successfully executed -just few events happened along the test execution (problems on the GNSS acquisition during the second flight, poor target reflectance due to the used materials...). Therefore the main objectives of this test, which were proofing the mechanical, electrical and SW system interfaces and demonstrating preliminary end-to-end capabilities, were achieved.

More in detail, with respect to the navigational aspect, the NS acquired data from the BA, magnetometer, LN200 IMU (RINS system was not integrated at the time of the tests) and EGNOS-GNSS sensors, providing a real-time loose-coupled magnetometer/INS/GPS (GPS stand-alone, EGNOS capability was switched off) solution. This solution was degraded by the several satellite in-and-out's (provoked by the sub-optimal antenna placement) which is well-known to have a severe impact on loosely-coupled schemes. Nonetheless, measurements can be post-processed in a close-coupled EGNOS-enabled BA/magnetometer/INS/GPS scheme, with the expectancy of improving the navigation results. On the second test campaign, a full-fledged navigation approach will be brought to the system, aiming at the UA control. The AIM approach is also envisioned for the second test campaign. Finally, no target geo-referencing was done in real-time, but it will once the closely-coupled processing will be completed.

With respect to the imaging results, the three tests showed a good performance of the subsystem. On the first test, the theoretical Ground Sampling Distance (GSD) provided by the sensor was verified for each of the heights achieved by the UA. For the 10m, 30m and 50m heights, GSD values were 1.8cm x 1.8cm, 5.5cm x 5.5cm and 9.2cm x 9.2cm, respectively. In addition, no image deformations were observed -therefore no geometric or thermal calibration is needed (figure 7). When analyzing the target recognition at different speed profiles, it can be seen that a fading effect is observed at all speeds ranging from 4 to 8 m/s. Further assessment needs to be done with human targets with respect to this test.

Finally, on the second and third flight, the person recognition was feasible at both flying heights. On support of this statement, a comparison between identical targets at different heights, i.e. different GSDs, is provided in the Appendix – reader can compare figure 8 vs figure 11, figure 9 vs figure 12 and figure 10 vs figure 13. It is planned for the project second iteration to implement an assisted-recognition mechanism, that is, an algorithm to highlight potential human targets and provide its ground position in real-time.

From both flights, a conclusion arises: on one hand, the lower altitude and the lower speed is executed, the better recognition can be done. But on the other hand, low height and speed require a longer mission time. Finally, depending on the platform endurance, long mission times could lead the mission to be flown in several parts, and thus affect SAR mission performance. It is therefore crucial for the system feasibility to determine optimal flying height and speed.

3.3 Further research

Next steps deal with the demonstration of EGNOS-based navigation suitability for UAV platforms and the use of redundant sensor as a fundamental condition to ensure robustness. This goal will be achieved with the incoming EGNOS-GNSS/RINS close-coupling scheme, aided by BA and MAGN, and its comparison against the reference RTK solution.

Beyond the accuracy and precision requirements, CLOSE-SEARCH will implement the AIM concept leading to a robust least-squares-based navigation filter i.e. resilient to eventual failures in *every* sensor, and in addition a new integrity frame for small UAV low-altitude platforms will be developed –actual integrity requirements are suitable for civil aviation platforms, but insufficient for close-range missions.

Finally, improvements on the user interfaces, body detection mechanisms and target management will be done to ensure end-to-end functionality as requested by the user, proofing CLOSE-SEARCH as a valid search tool for SAR missions.

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5. ACKNOLEDGEMENTS

The research leading to these results has received funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement n248137.

The project coordinators sincerely thank all partners in the CLOSE-SEARCH consortium (Asociación de la Industria Navarra, Pamplona; DEIMOS Engenharia, Lisboa; École Polytechnique Fédéral de Lausanne, Lausanne; Institut Cartogràfic de Catalunya, Barcelona; Direcció General de Protecció Civil, Barcelona) for their work on the project and specially thank the IG’s Integrated Geodesy and Navigation unit members -this paper is the result of everybody’s work.

6. APPENDIX: PICTURES, PLOTS AND THERMAL IMAGES

Figure 5: AIN’s UAR35, the Unmanned Aerial Vehicle (UAV) used in CLOSE-SEARCH

Figure 6: Thermal passive target used during the first test campaign in CLOSE-SEARCH

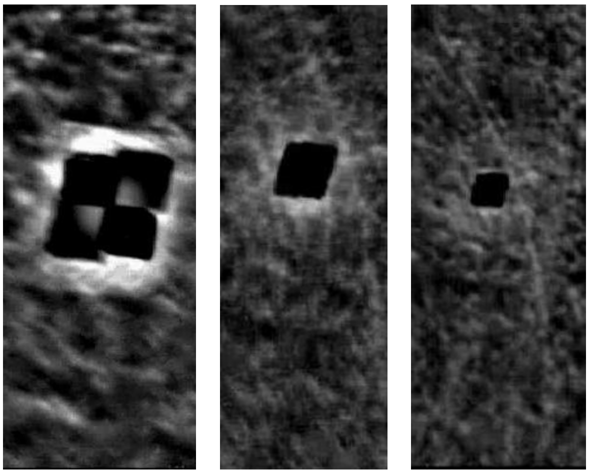

Figure 7: Thermal image of the passive target, from left to right: GSD = 1.8cm x 1.8cm, GSD = 5.5cm x 5.5cm, GSD = 9.2cm x 9.2cm

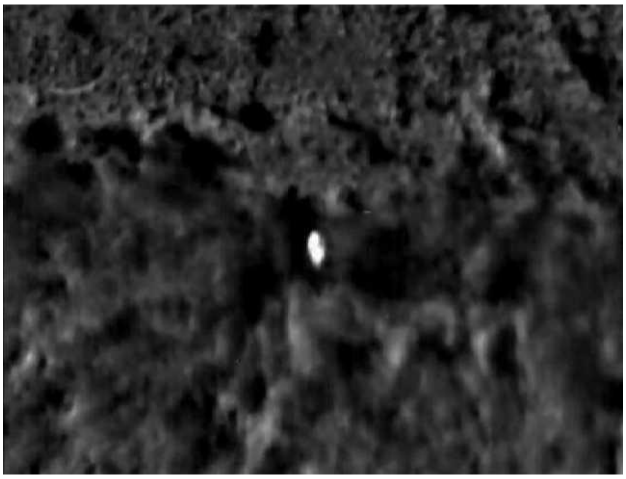

Figure 8: Thermal image of Person 1, GSD = 5.5cm x 5.5cm

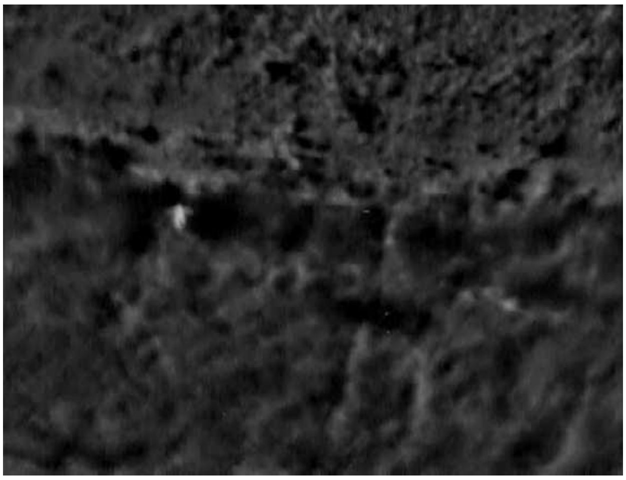

Figure 11: Thermal image of Person 1, GSD = 9.2cm x 9.2cm

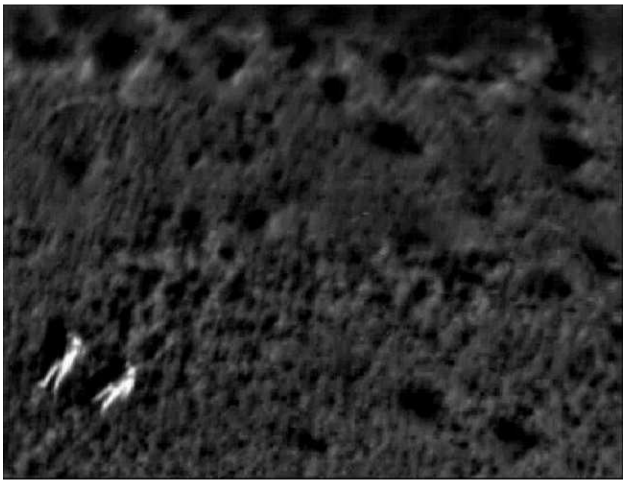

Figure 9: Thermal image of Person 2, GSD = 5.5cm x 5.5cm

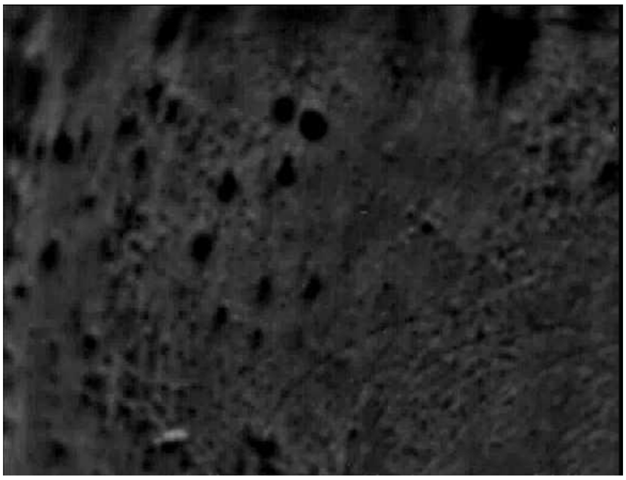

Figure 12: Thermal image of Person 2, GSD = 9.2cm x 9.2cm

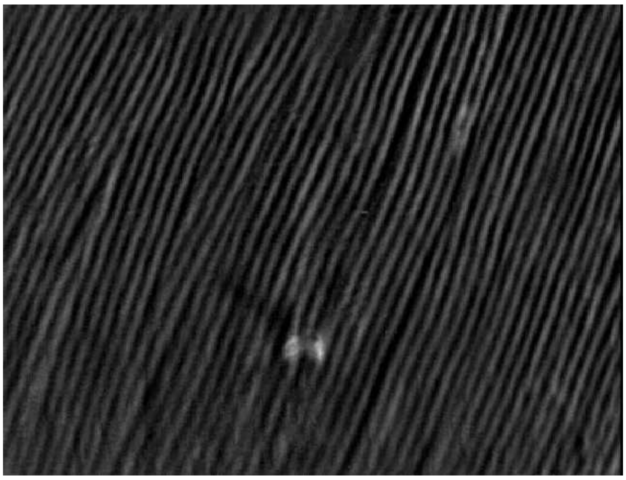

Figure 10: Thermal image of Person 3, GSD = 5.5cm x 5.5cm

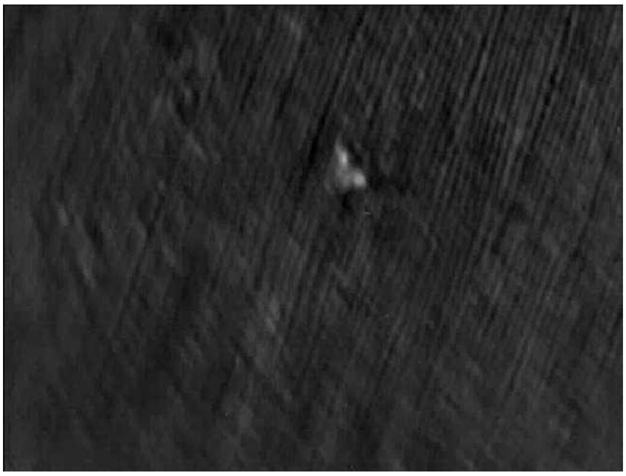

Figure 13: Thermal image of Person 3, GSD = 9.2cm x 9.2cm