Synchronised Data Acquisition for Sensor Data Fusion in Airborne Surveying

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***Abstract*—An existing facility for data acquisition in aerial surveys is presented. It contains a laser radar, an infrared camera and a video camera. The system supports synchronisation of sensor data, even when the sensor does not inherently offer that feature. This allows data from different sensors to be merged and processed together. The necessary temporal referencing is achieved by specialised hardware implemented in a Field Programmable Gate Array, which also serves to acquire data from the IR camera. The usefulness of FPGAs for this purpose is demonstrated. The possibilities FPGAs offer are shown up, and future extensions of the system are presented.**

Keywords: Data acquisition, geosurveys, FPGA

I. Introduction

Remote sensing is a well-established and wide research field. Its origin and most of its applications lie in cartography and other geosciences. For more than a decade, fusion of data from different sensors has been a research topic in this field (see for instance [1]). Typically such work involves satellite or aerial data purchased from or donated by commercial companies which are already georeferenced. If necessary, data from different sources are registered manually with respect to each other. This process is rarely remarked on, but in some cases considerable discrepancies in the location reference have been found [2].

The institute FGAN–FOM researches both processing methods for imaging sensor data and the sensors themselves. Multi-sensor data processing has been a research topic for some years. The sensor and data acquisition system which will be presented in this paper was specifically designed to facilitate the fusion and common processing of data from different sensors. It is being used to acquire data for a wide range of applications including vehicle recognition, mapping of urban areas and image-based navigation [3]–[6]. For that purpose it needs to be versatile and has to meet a number of requirements. In order to allow measurements in different situations called for by the various applications, the sensor system is mounted on a helicopter. This allows high-accuracy measurements at low altitudes and flight speeds as well as more common aerial surveys at medium altitudes.

The aim of accurate multi-sensor data fusion places special demands on the synchronisation of the resulting data. In an ideal sensor system it would be possible to operate all equipment by a common external clock, as is for instance done in TV recordings. However, in a heterogeneous multi-sensor system comprising sensors which are not designed to operate together, no such off-the-shelf solution exists. In work using the predecessor of the sensor system described here, which did not have a synchronisation mechanism, registration of data from different sensors had to be performed manually by estimating changes in aircraft orientation from the infrared camera data [7], [8].

In this sensor system, synchronisation is achieved by accurate temporal referencing of the main sensors, the laser scanner and the IR camera. In the following, the word “synchronisation” shall be used in this loose sense, rather than for the external clocking of sensors which is not possible in this case. The temporal referencing is performed with the help of special logic developed at FGAN–FOM and implemented in a Field Programmable Gate Array (FPGA).

The following section describes the sensor system and its operation. Section III presents the synchronisation mechanism and the functionality implemented in the FPGA. The last section summarises the paper and presents further work to be done.

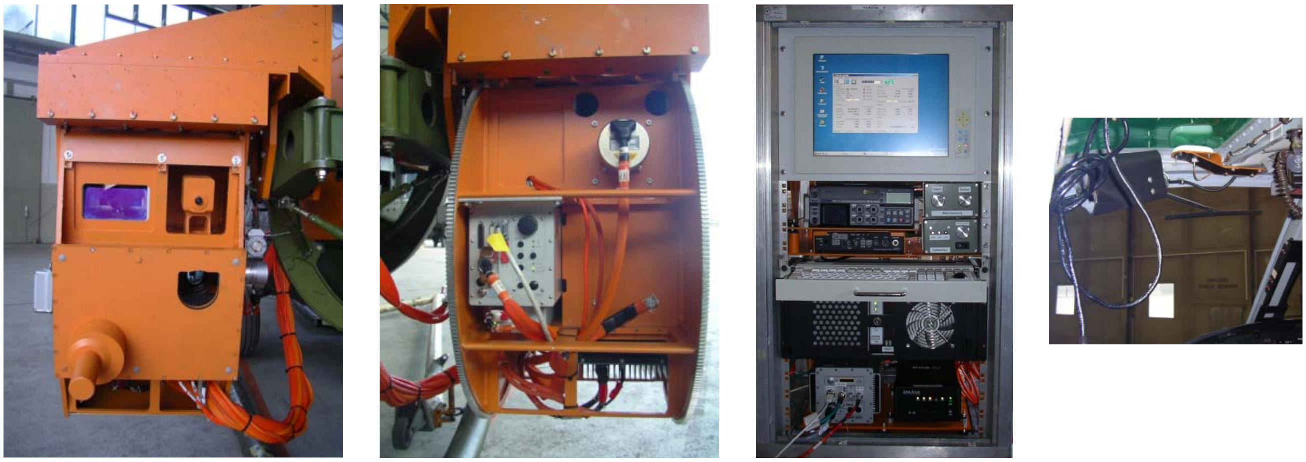
II. The sensor system

The data acquisition system described here is designed to be mounted in a helicopter of the type Bell UH-1D. It is composed of a sensor platform and a rack inside the helicopter for data acquisition and control, which will be described in the following subsections. The PC contained in the rack runs software operating the sensor system. It is described in the last part of this section.

A. Sensor platform

Several sensors are mounted on a platform which is attached to the side of the helicopter. It can be seen in Figure 1 (a) and (b). The sensor platform can be tilted during the flight so as to allow measurements with different perspectives, e.g. both looking vertically down and looking forward obliquely. A rotary encoder connected to the axis of rotation measures the current position.

Attached to the sensor platform is an aerial laser scanner of the type Riegl LMS-Q560 [9]. It is a line scanner, i.e. it repeatedly takes a set of distance measurements perpendicular to the aircraft’s flight direction. The second dimension of the height profile is added by flying over a piece of terrain. The LMS-Q560 digitises the shape of the returning laser pulses, and allows multiple distances to be obtained from each



(a) Front of the sensor platform. The rectangular window is part of the Riegl LMS-Q560 laser scanner. The big lens behind the calibration device (middle) belongs to the IR camera, and the small lens (top right) to the video camera.

(b) Back of the uncovered sensor platform. The back of the IR camera and the IMU (cylindrical, top right) can be seen.

(c) Front view of the rack. In addition to the PC, there is the video recorder (middle) and the Riegl data recorder and Applanix PCS (bottom).

(d) The GPS antenna (on orange carrier) is situated under a top window inside the helicopter cabin

Figure 1. Photos of the sensor platform (a, b), the electronics rack (c) and the position of the GPS antenna (d).

measurement by offline analysis. It is highly configurable: The laser pulse rate, the number of measurements per scan line and the angle increment between measurements can be adjusted. Typical values are a pulse rate of 100 kHz and 600 measurements with an increment of 0.1°. The laser scanner's field of view perpendicular to the flight direction is variable, but is usually chosen as its maximum of 60°.

The second main sensor on the sensor platform is an AIM 640 QMW infrared camera [10]. It operates in the wavelength range of 3–5 μm and has a resolution of 640 by 512 pixels. Its image detector is a Quantum Well Infrared Photodetector (QWIP) focal plane array, which is cooled to 80 K (-193 °C) by an integrated Stirling cooler. Its lens gives it a horizontal field of view of 40°.

The IR camera has to be calibrated after cool-down to correct for inhomogeneities in the detector. Typically a two-point correction is performed which equalises both gain and offset across all pixels. This requires consecutively putting two objects of homogeneous temperature in front of the camera which cover its field of view. To facilitate this, and to allow repeating this correction in flight, a calibration device built at FGAN–FOM is attached to the sensor platform. It contains two metal plates of which one is heated, which can be swivelled in front of the IR camera.

The two other sensors on the sensor platform are a video camera and an inertial measurement unit (IMU). Since the video camera serves to record ground truth, its lens was chosen to match the field of view of the laser scanner of 60°as closely as possible. It has a horizontal field of view of 53°. The IMU is part of the inertial navigation system which is described in the following section.

B. Recording and control devices

A rack in the helicopter cabin contains power supply units, data recording devices, a position computation system (PCS) and a PC which controls the other devices. It is depicted in Figure 1(c).

The position and orientation of the aircraft is determined by the inertial navigation system Applanix POS AV 410 [11]. It consists of the IMU on the sensor platform, a position computation system for combined inertial and GPS position determination, and a GPS antenna mounted under a top window inside the helicopter cabin (see Figure 1(d)). The IMU accurately measures linear and angular acceleration at a rate of 200 Hz. The PCS computes the aircraft's orientation and its short-term position changes from the IMU data and uses the GPS data as a reference. Data from these two sources are reconciled using a Kalman filter. The accurate position and orientation data this navigation system provides are extremely important for composing a height profile from line laser scanner data. The navigation system is also central to the temporal referencing which will be described below.

Two further devices mounted in the rack are a video recorder and a data recorder for the laser scanner. The video recorder receives an analogue signal from the video camera, digitises it and records it on tape, and patches it through to a monitor which can be seen by the pilot. This allows the pilot to see the view from the sensor platform and to fly according to specifications.

The laser data recorder is part of the laser scanner system. The laser scanner transmits digitised laser pulses to the recorder via a digital serial link. The recorder contains two hard disks on which the data are saved without a file system. They are later copied to the PC via a USB interface.

The PC in the rack serves to control the whole sensor system and to record data from the IR camera and the navigation system, as can be seen in Figure 2. It contains an extension card carrying a Field Programmable Gate Array (FPGA) [12] in which custom logic is implemented. Data are transmitted from the IR camera to the FPGA card over a parallel digital interface. After compression and buffering on the FPGA, those data are read by the host PC via a 64-bit PCI bus using direct memory access (DMA). The data rate from the IR camera is 15.6 MB/s.

In order to operate the sensors, the PC is connected to them through various interfaces. It communicates with the PCS via an Ethernet connection and a serial interface. The latter serves to transmit the sensor platform tilt angle, which is not possible via the Ethernet interface. A program from the navigation system's manufacturer Applanix allows to view the current position, the flight trajectory and status information. The IR camera is connected to the PC via an RS232 serial interface and is controlled by a software program from the manufacturer. This software is used to initiate the non-uniformity correction procedure. The calibration device on the sensor platform which is necessary for this procedure is operated with a control box also mounted in the rack. The laser scanner and its dedicated recorder are connected to the PC over Ethernet, via a network switch. They are operated by the overall control software developed at FGAN–FOM, which is described in detail in the following section.

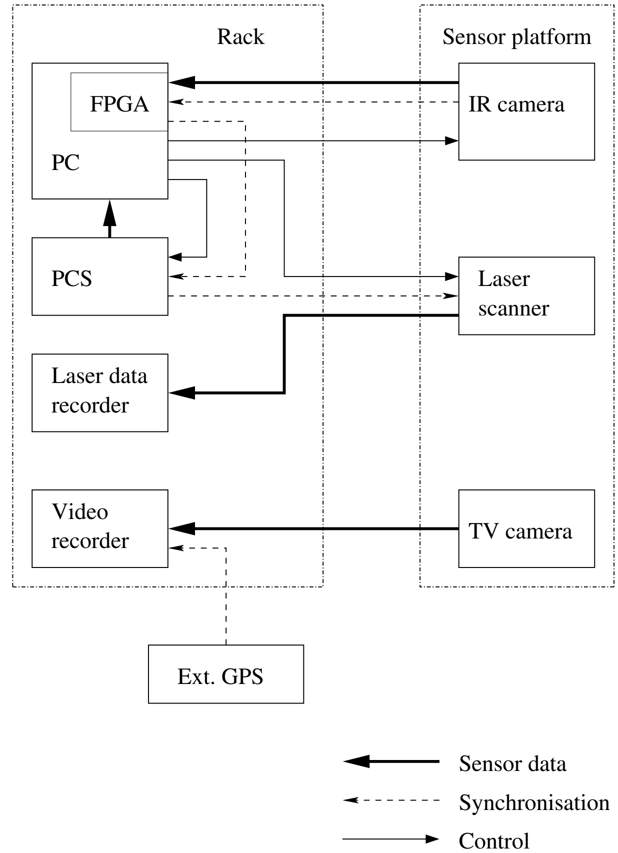


Figure 2. Data transmission, synchronisation and control paths in the data acquisition system.

C. Control software

The sensor system comprises several different sensors made by different manufacturers and not designed to operate together. Each of the sensors comes with software provided by the manufacturer for control, configuration and operation. The laser scanner and the navigation system have a large number of parameters which can be adjusted and which may have to be changed between measurements. Adjusting the parameters and operating the sensors can be done using the manufacturers' control programs. However, a helicopter is a very unusual working environment for a scientist. One's concentration is disturbed by noise and vibrations, adjustment of sensor parameters has to be completed before flying over the next object to be measured, and measurements cannot easily be repeated if something goes wrong. To use a multitude of interactive programs in this context is cumbersome and error-prone. For that reason a program for overall control of the sensors was created at FGAN–FOM.

This control program, which is called `fusiondaq`, performs a number of tasks for all sensors except the video camera, which cannot be controlled from a PC. The user interacts with `fusiondaq` by typing text commands. Its settings are contained in two plain text files. The configuration file tells `fusiondaq` how to connect to the different sensors. A parameter file contains sets of sensor parameter values with which the sensors are configured when the operator chooses to do so.

The program `fusiondaq` is organised in three threads. Upon startup, it initialises itself and the sensors. This involves deactivating the laser scanner's laser, which is switched on after power-up. `fusiondaq`'s second thread is started which reads the tilt angle of the sensor platform from the rotary encoder. This thread continually transmits this angle to the PCS. The third thread is started which sends commands to the PCS and receives the position, orientation and other data from it. The FPGA, which is situated on a PCI card in the PC, is configured with the logic design which allows it to receive data from the IR camera. A separate program which performs the transfer of the IR data from the FPGA card to the hard disk is also started during the initialisation of `fusiondaq`. It is controlled by `fusiondaq` via user datagram protocol (UDP) packets.

Using `fusiondaq`, data acquisition can be started and stopped for all sensors at a time. Sensor readout is started in an order taking interdependencies into account, and stopped in the opposite order. The recording of data from the navigation system is started first, as they are required for analysis of the laser data and synchronisation of the IR images.

`fusiondaq` also serves to manage different sets of sensor operating parameters. This allows to quickly change the operating modes of the laser scanner and the type of readout data from the navigation system between different measurements. The parameter sets are stored in a plain text parameter file which is read by `fusiondaq` during startup. Later the user can apply a parameter set by typing a command and the label which identifies the parameter set.

The last but not least function of `fusiondaq` is to generate a log of all measurements. All messages output by `fusiondaq` and messages received from the sensors are written to a log file. User commands are also logged, together with the time at which they were entered. The contents of the configuration and parameter file are output and logged when `fusiondaq` starts up. This makes the log file self-contained. As a consequence, only the log file and the sensor data are required for later analysis, and any operating errors which may have occurred can be reconstructed.

III. TEMPORAL SYNCHRONISATION

The purpose of the sensor system as described in the previous section is acquiring data from the three sensors, the laser scanner, the infrared camera and the video camera. It also allows georeferencing the data using the position data from the inertial navigation system. However, a main research topic at FGAN–FOM is sensor data fusion. The data acquisition system was therefore designed to facilitate merging data from the different sensors with proper time referencing. This section presents how this has been achieved.

A. Overview

An overview of the synchronisation is presented along with the readout and control data paths in Figure 2. Central to the temporal referencing is the navigation system, which receives accurate time information from its GPS receiver.

The time referencing of the laser scanner data is a feature of the laser scanner system itself. Because it is a line scanner, its data can only be analysed together with position data from the navigation system, and combining the two requires matching them in time. For this reason, the laser scanner is designed to receive GPS data packets and 1 Hz pulses from the navigation system and use the corresponding time to tag its data. This feature was used as provided and required no customisation.

Unlike the laser scanner, the infrared camera does not inherently allow time registration of its frames. Nonetheless, the fact that the IR data are recorded with the help of an FPGA makes this easily possible. The digital data interface of the IR camera contains line and frame sync data which are used for frame grabbing. The frame sync pulse is fanned out inside the FPGA and output on a different connector. The navigation system has two so-called event inputs. When an electrical pulse arrives on one of these inputs, the corresponding time is logged with sub-millisecond accuracy. The frame sync pulse from the FPGA card is connected to one of these event inputs.

The data sets containing the event times are part of the navigation system's data stream, which is transmitted to the PC via Ethernet and recorded on the PC's hard disk. The logic on the FPGA is designed to output the frame sync pulse only when IR data are being recorded. As a consequence, there is a one-to-one correspondence between recorded frames and event times. This makes it trivial to assign time stamps to all camera frames.

The video recorder is not connected to the rest of the data acquisition system. Its internal clock is set using a separate portable GPS receiver before each measurement flight. The corresponding time code is embedded into the digital video recording. This time information can be retrieved after the video data have been transferred to a PC, which makes it possible to synchronise the video camera frames as well.

B. Custom logic

As has been stated in the previous sections, data acquisition and temporal referencing of the IR data is performed by custom logic implemented in a Field Programmable Gate Array (FPGA). This section will take a more detailed look at its functionality and present the advantages of using FPGAs for data acquisition.

Figure 3 shows how the IR data acquisition works. Data originate from the the camera and are ultimately saved to the PC's hard disk. This happens by way of the FPGA. The main components of its design are a camera interface, a compression unit, a FIFO buffer and an interface to the local bus on the FPGA card (which leads to the PC's PCI bus). The camera interface determines when valid data are received from the camera, sets flags indicating the start of a frame and of a pixel line and ensures readout starts at the start of a frame. It also performs the important task of patching the frame sync signal through, which is fed into the event input of the PCS.

The camera interface passes the data on to the compression unit. This unit implements a lossless difference compression. Whenever possible, two 7-bit differences between successive pixel values are stored in each 16-bit data word rather than one 14-bit absolute pixel value. The remaining two bits in a data word are used to indicate compression, as well as the start of a frame and pixel line. This method achieves a compression ratio of 1.7 to 2 depending on how strong contrasts in the scene are.

Most of the space on the FPGA is taken up by a large FIFO buffer. It serves to equalise fluctuations in the PCI bus data transfer rate due to the fact that the operating system used, MS Windows XP, is not a real-time operating system. The buffer also handles the transition from the camera interface and compressor, which are synchronous to the clock of the camera, to the local bus interface which is synchronous to the local bus clock. Finally, the local bus interface transmits the data to the PCI interface of the FPGA card.

Despite the compression, it is nontrivial to transfer the data over the PCI bus reliably. For that purpose, two different DMA channels are used in turn — while transfer is in progress over one channel, the next transfer is set up. IR data are written to the PC's hard disk by mapping a file into memory, thereby utilising the operating system's efficient paging mechanism.

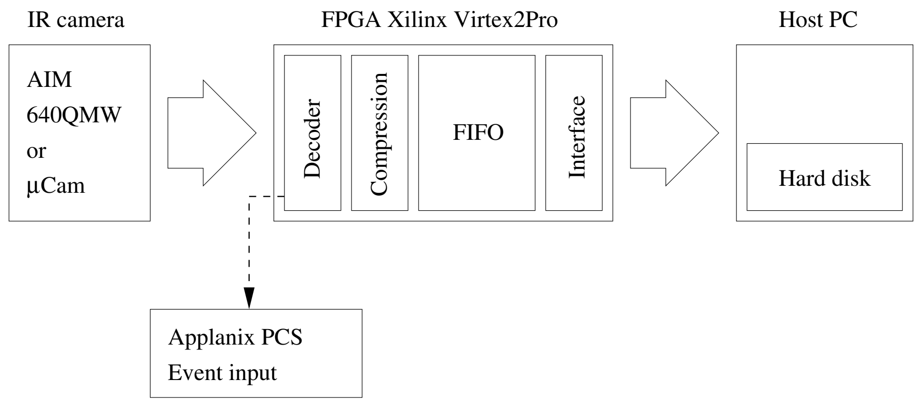


Figure 3. Block diagram of the IR data acquisition and synchronisation.

The digital interface of the camera AIM 640 QMW is peculiar to this series of IR cameras, and compatible frame grabbers are not available off the shelf. This fact alone makes the use of custom hardware necessary. But there are other advantages of using FPGAs. FGAN–FOM is a research institute dedicated to evaluating sensors and developing processing methods for imaging and other sensors. Both aims make it desirable to be able to exchange sensors without having to build a whole new system. FPGAs offer that possibility.

A different FPGA design has been developed for acquiring data from a different IR camera from the same manufacturer, the AIM μCam [13]. Its interface consists of three 7-bit serial links. The frame sync indicator is one bit in one of the serially transmitted data words, rather than a separate signal as in the case of the AIM 640 QMW. However, only the camera interface part of the FPGA design had to be modified to integrate the new camera. It generates and outputs a frame sync signal and thereby remains compatible to the remainder of the data acquisition system. This attests to the great versatility and usefulness of FPGAs, which has also made them popular in other fields of research such as elementary particle physics.

IV. Summary and Outlook

This paper has presented a sensor system containing a laser scanner, an infrared camera, a video camera and an inertial navigation system. It was designed to allow fusion and common processing of data from the two main sensors, the laser scanners and the infrared camera. For that purpose, data are accurately referenced in time. This is done with the help of the navigation system which contains an accurate clock synchronised by its GPS receiver. Custom logic implemented in a Field Programmable Gate Array (FPGA) is used to acquire data from the IR camera and to perform synchronisation of these data. Due to the versatility the FPGA provides, two different IR cameras can be used interchangeably, without modifying the rest of the system.

It has been shown that FPGAs can greatly facilitate integrating heterogeneous sensors into one system. The synchronisation approach presented above could easily be adapted to other types of sensor. Regardless of how a sensor's data are acquired, an FPGA can be adapted to receive synchronisation information in a variety of forms. It can generate an event pulse for the Applanix PCS, or output synchronisation information in a different form suitable for a different device. The sensor system which has been presented will be extended to other sensors in the months to come. Another infrared camera from a different manufacturer will be integrated as a further alternative to the two cameras by AIM. Data acquisition from this camera works via a FireWire interface without involvement of the FPGA, but synchronisation will again use it. Furthermore, a high resolution video camera will replace the current one and will be synchronised similarly to the IR cameras. It is envisaged that the system will continue to be extended to include up-to-date sensors.

An extension of our synchronisation approach to several aircraft or vehicles is not planned in the immediate future, but is nonetheless feasible. In order to obtain the position and orientation of all sensors, every vehicle would have to carry an inertial navigation system. Synchronisation between those vehicles would be achieved by logging some event pulses both locally by the INS of the same vehicle and transmitting it by a wireless link to the others. These pulses could be either synchronisation signals from one of the sensors or be generated by an FPGA specifically for inter-vehicle synchronisation. If temporal accuracy is to exceed the latency of the wireless link, this latency can be measured by echoing the arriving synchronisation pulses back to the sender.

If more than a few vehicles are involved, the number of synchronisation signals may exceed the number of event inputs of the navigation system. (The same problem may occur if a large number of sensors are to be synchronised on a single platform.) This can be easily solved by custom logic implemented in an FPGA. The multiple synchronisation signals would be timed by a clock running internally in the FPGA. This clock would be synchronised with the navigation system by periodically sending an event pulse. The versatility of FPGAs permits a great deal of adaptations and extensions for a variety of applications.

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