FuSeOn: a Low-cost Portable Multi Sensor Fusion Research Testbed for Robotics

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Abstract. Nowadays, the utilization of multiple sensors on every robotic platform is a reality due to their low cost, small size and light weight. Multi Sensor Fusion (MSF) algorithms are required to take advance of all the given measurements in a robust and complete manner. These high demanding developed algorithms need to be tested under real and challenging situations and environments. To the knowledge of the authors, none of the available datasets fulfills are fully suitable to be used for MSF applied to Robotics, due to the lack of multiple sensor measurements provided by light weight, small size and low cost sensors; due to their restricted motions (typically planar movements); or to their limited environmental conditions.

The contributions of the paper are twofold. First, a low-cost portable and versatile testbed has been developed for MSF research with various types of sensors. Second, a group of datasets for MSF research for Robotics have been made public as a common framework for algorithm testing after a comparison with the existing databases in the state of the art, highlighting the differences and advantages of the one presented in this paper, that are: low-cost sensors for general use on Robotics, fully 3 dimensional movements (six degrees of freedom), as well as challenging indoor and outdoor small and large environments.

Keywords: Multi Sensor Fusion - Datasets - Robotics - Testbed

1 Introduction

The latest advances on Micro-Electro-Mechanical Systems (MEMS) and the diminishing size, weight and cost of sensor technologies, are motivating the installation of more sensors in all the developed robots. In the particular case of multirotor type Unmanned Aerial Systems (UAS), this is a tangible reality. For example, the old Asctec Autopilot[1] has a single Inertial Measurement Unit (IMU), compared to the new cutting-edge autopilot, the Asctec Trinity[2] with triple redundant IMUs. Another example is the famous Open Hardware PixHawk Autopilot[3], which includes double redundant IMUs.

[1] http://wiki.asctec.de/display/AR/AscTec+AutoPilot
[2] http://www.asctec.de/en/asctec-trinity/
[3] https://pixhawk.org/modules/pixhawk

In the past years, the information given by every sensor was treated individually for very limited purposes (e.g. an optical flow sensor onboard a UAS to measure the ground speed, that reports a wrong measurement if the UAV is hovering over a moving obstacle). Nowadays, the measurements given by all the sensors are analyzed together by means of Multi Sensor Fusion (MSF) algorithms to improve the state estimation (of the robot and / or its environment) and to reduce the effect against the failure of the sensors (e.g. if the onboard IMU measurement is fused with the optical flow measurement, the robot could infer that the obstacle is moving under it).

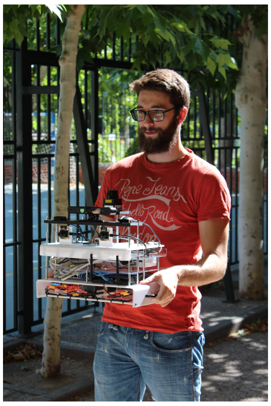


Fig. 1. The FuSeOn testbed during an experiment.

MSF algorithms have a high number of difficult requirements, which convert the development of these algorithms a challenging task that still continue to be under research. They require to be able to manage a big amount of information because each sensor outputs its raw measurements that need to be processed. They have to deal with sensors that work at a different rates, with different time delays, and with different measurement noises. The robot state might not be calculated directly using the sensor measurements, having to infer it. MSF algorithms must detect sensor failures, processing this information in a special manner. To take advance of the MSF algorithms, they are required to be fast enough to work in real time. Good precision and performance in the state estimation is also compulsory. Finally, MSF algorithms have to deal with real systems that typically have non-linearities in their erroneous or incomplete models. This implies that an auto-calibration capability of the sensors and the models is a desired feature on these algorithms that allows to improve their precision.

There exist multitude works in the field of Multi Sensor Fusion, with a tangible growth in the last years. Some works are related to the well studied Multi GPS-INS Fusion [10, 18]. In the last years, the computer vision has experienced a new renaissance with new localization and mapping algorithms, specially with monocular and RGB-D cameras. To recover the scale factor with monocular cameras, a lot of works have been published on Visual-INS Fusion [20, 13] with a promising success.

The final objective of most of the works on Multi Sensor Fusion is to apply them to the Robotics [6]. Multi Sensor Fusion is specially useful in UAS, where its 6 DoF movement is hard to be tracked and estimated. Combining UAS with Visual-INS sensors is a current trend [2, 1], but most advanced works include in the sensor fusion algorithm, the information given by many other sensors [7, 19].

To ease the research on Multi Sensor Fusion, and to be able to compare different proposed algorithms, datasets are specially useful. Nevertheless, to the knowledge of the authors, none of them fulfills completely the requirements highlighted in Section 3.

As the authors believe on the Open Science concept [3], this paper introduces two useful contributions for the scientific community:

The first one is the hardware and software design of the FuSeOn testbed (Section 2), a specifically designed low cost testbed for the research on Multi Sensor Fusion for Robotics. Its portability permits to easily be carried everywhere by a person to acquire data or to test his algorithms with any desired movement. Its modularity and versatility ensure the possibility to reconfigure it or add it new features or sensors with a low effort. The hardware design is detailed to serve as a starting point for other researchers interested on working on Multi Sensor Fusion with enough resources to build their own testbed. The software sources has been also made available to the scientific community.

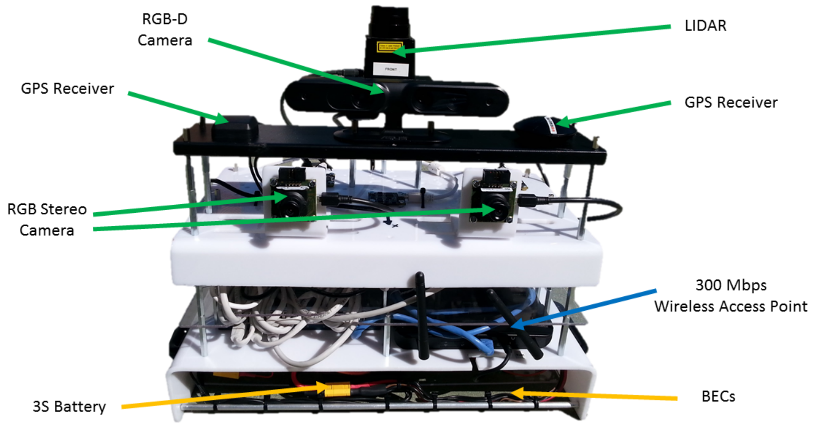
The second contribution of this work is double. First of all, the state of the art available datasets are analyzed in Section 3. Then, in Section 4, a collection of datasets for the research on Multi Sensor Fusion for Robotics is presented, aimed to researchers without enough resources to build their own testbed, as well as, to serve as a reference to compare the developed algorithms by testing them under the same conditions.

2 System Description

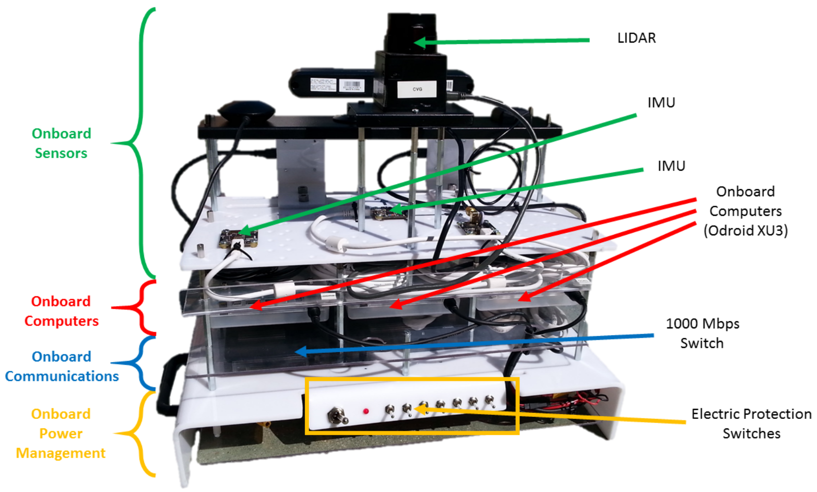
The FuSeOn testbed (Figure 2) has been designed taking into account the following requirements:

- It has to be mobile and portable, to be able to move it anywhere to acquire and process the data in order to allow the researchers to work in a very wide number of scenarios. A person has to be able to carry it with a small effort, so that the FuSeOn board can reach the same places than the person.
- It has to be modular and versatile enough to be able to be modified, in order to add new sensors, computers or to reconfigure it in case of a new research need. Additionally, must be mechanically simple to maintain it with the less possible effort.
- Its endurance time has to be enough for most of the MSF tests (e.g. typically, UAS flights last less than one hour).
- The usage of the testbed has to be simple, allowing the researchers to easily control, monitor and supervise not only the system, but also the ongoing test.
- Its computational power has to be enough to run most of MSF algorithms (equivalent to a current average laptop).
- It has to be cost-effective.

The requirements cited above have been satisfied thanks to its design using methacrylate layers (Figure 2), in which each of the parts of the board has been divided, allowing the desired modularity and versatility, as well as easing its maintenance. Its small size (less than $40 \times 25 \times 40$ cm) and light weight (less than 4 kg) let a person to carry it everywhere (Figure 1). Its power system makes the FuSeOn board fully portable, as well as, giving it an endurance time higher than one hour with the same battery. Its communication system permits a simple remote usage, control, monitoring and supervision by means of the ground computers, as well as the connection of the testbed with the Internet. The computational power needs are satisfied with three small onboard computers added to the ground computers, plus the capability of cloud computing. Its software has also been very carefully designed setting an easy process management and inter processes communication. Last but not least, the main part of the cost of the platform is due to the installed sensors, being then cost-effective.



(a) Front



(b) Back

Fig. 2. The FuSeOn testbed.

The FuSeOn testbed is divided on three subsystems: The **FuSeOn Board** is the portable and mobile part of the testbed, in charge of the sensing and the real time processing of the sensed data. It includes the onboard sensors (Section 2.1), the onboard computers Section 2.2), and the onboard power management (Section 2.3). The **FuSeOn Ground Stations** are a semi-portable part of the testbed formed by the ground computers (Section 2.4), which mission is the interaction with the user for controlling and supervising the FuSeOn board, as well as the heavy (and low frequency) processing of the sensed data. Finally, the **FuSeOn Communication System** allows the communication within the FuSeOn system and with the external networks (Section 2.5).

The enumeration of the specifications of each device installed on the FuSeOn testboard is out of the scope of this paper and can be consulted on the Internet following the links provided on the footnotes.

2.1 Onboard Sensors

The FuSeOn includes four proprioceptive sensors (gyroscopes and accelerometers of two IMUs) and six exteroceptive sensors (compasses of two IMUs, two RGB Cameras, one RGB-D Camera and one LIDAR), all of them with an Universal Serial Bus (USB) interface, what eases the hardware design:

- **Global Positioning System (GPS) Receivers**: Two different GPS receivers have been installed for MSF challenges on different locations on the FuSeOn: A Phidgets Inc, GPS receiver (P/N: 1040)[4] and a US GlobalSat Inc, GPS receiver (P/N: BU-353S4)[5]. The main difference between these two sensors is the update rate, being the Phidgets 1040 ten times faster than the US GlobalSat BU-353S4.
- **Inertial Measurement Units (IMU)**: Similarly to the GPS receivers, two different IMUs were installed on the FuSeOn: The main IMU sensor, a Phidgets Inc, Spatial 3/3/3 HR (P/N: 1044)[6] was installed in the center of coordinates of the FuSeOn. An additional Phidgets Inc, Spatial 3/3/3 (P/N: 1042)[7] was also installed on away its center of coordinates. The Phidgets 1044 is much more precise than the Phidgets 1042.
- **RGB Cameras**: Two uEye cameras, UI-1221LE-C-HQ[8] were installed on the FuSeOn creating a stereo pair. The decision to mount two similar cameras in a stereo pair configuration is to allow the use of both one or two monocular algorithms, as well as a stero algorithm for visual state estimation.
- **RGB-D Camera**: An ASUS XTion Pro Live[9] has been installed on the FuSeOn, aiming to the same scene than the two RGB cameras.

[4] `http://www.phidgets.com/products.php?product_id=1040`
[5] `http://usglobalsat.com/p-688-bu-353-s4.aspx`
[6] `http://www.phidgets.com/products.php?product_id=1044`
[7] `http://www.phidgets.com/products.php?product_id=1042`
[8] `https://en.ids-imaging.com/IDS/spec_pdf.php?sku=AB.0010.1.22500.00`
[9] `https://www.asus.com/Commercial_3D_Sensor/Xtion_PRO_LIVE/specifications/`

– **LIDAR (laser rangefinder)**: A Hokuyo URG-04LX-UG01 has been installed on the FuSeOn.

2.2 Onboard Computers

Three Odroid XU3 micro computers[10] were installed to receive and process in real-time the information given by the mounted sensors. These computers, combine a low-price (less than 200€), small size and weight (less than 10 x 8 x 2 cm. and 200 g.) and good performance (higher than any smartphone on the market), in addition to five USB ports to connect all the sensors. All computers run Linux LUbuntu 14.04.2 LTS for ARM devices.

2.3 Onboard Power Management

A 3S 5000 mAh 20C LiPo battery provides the system with enough energy to power all the sensors, onboard computers and onboard electronics during more than one hour, allowing the portability and mobility of the FuSeOn board. The full electric circuit is protected by a several switches. The installed Battery Eliminator Circuits (BECs) have the mission of stabilizing the non-constant voltage given by the battery to a constant voltage that the onboard electronics require to work.

2.4 Ground Computers

The monitoring and supervision of the FuSeOn board, as well as the user interaction, is done by means of one or more ground computers mechanically detached to it, connected to the FuSeOn network by means of a WiFi adapter (Section 2.5). In addition, these computers can be used to run low frequency (less than 10 Hz.) heavy computational processes that the onboard computers are not able to. The ground computers run Linux Ubuntu 14.04.2 LTS.

2.5 Communication System

The communications system of the FuSeOn has two main objectives: First, it has to make available with the smallest possible delay all the sensor measurements in all the computers (onboard and ground computers) within the FuSeOn network. Secondly, it has the mission to communicate all the computers within the FuSeOn network with other networks to increase its capabilities, allowing then the use of advanced networking features like cloud computing or the Internet of things (IoT).

The onboard computers are connected in a wired network by means of a 1000 Mbps switch, minimizing the delays. An onboard 300 Mbps Wireless Access Point connected to the switch, creates its own WiFi a/b/g/n network, allowing

[10] `http://www.hardkernel.com/main/products/prdt_info.php?g_code=G140448267127`

the ground computers to have fast access to the FuSeOn network. Finally, a ground router enables the communication between the FuSeOn network with other networks.

2.6 Software

The software developed for the FuSeOn testbed uses ROS[11] as middle-ware, what not only eases the communications and management of processes, but also is a trend in the scientific community, being a multitude of software packages available ready to be used. A Plug & Play philosophy eases the use of the FuSeOn testbed.

Each sensor has its own ROS package to read the measurements given by the hardware, publishing them into a predefined ROS topic. The connected devices to the onboard computers are managed by udev, the device manager of the Linux kernel, by means of udev rules that launch Linux scripts to run the sensor drivers when attached to the onboard computer. A Devices Manager ROS node, running on a master onboard computer, manages and supervises the status of all the sensors and computers.

3 Available Datasets Comparison

To the knowledge of the authors, there is no complete and specific public dataset for the research on Multi Sensor Fusion applied to small-size or low-cost robotics (including UAS).

Table 1 shows a summary of the most famous state of the art available datasets, highlighting their main features. Some of these datasets, have a reduced number of available sensor measurements (because they are specific for the research in a concrete area); in some others, the movement of the testbed is limited (e.g. typically ground mobile robots only have three degrees of freedom).

With few exceptions, the environment of the datasets is not challenging enough in terms of MSF (e.g. typically transitions between indoor and outdoor environments are not available). In addition, nearly all of the most complete accessible datasets include measurements given by very expensive and heavy sensors, that would unlikely be mounted on every robot (e.g. a multirotor UAS cannot carry a heavy and expensive 3D Laser Scanner). Finally, some of the available datasets include Ground Truth. However, they are the measurements given by a high-precision sensor (e.g. a Motion Capture System) as well as the building plans, in indoor environments. In outdoor environments, the Ground Truth is provided by high-precision and high cost GPS-INS measurements (like D-GPS), as well as 3D laser scanner measurements.

[11] `http://www.ros.org/`

Dataset	Description[1]
TUM RGB-D [17]	A variety of **indoor** environments Microsoft Kinect: RGB-D images (30Hz, 640×480) and accelerometer data. **GT**: Sensor trajectory by motion capture system `http://vision.in.tum.de/data/datasets/rgbd-dataset`
NYU Depth v1 [15] & v2 [14]	A variety of **indoor** environments Microsoft Kinect, and a subset of the video data is accompanied by dense multi-class labels. `http://cs.nyu.edu/~silberman/datasets/`
CMU Visual Localization [12]	Multi-environment **outdoor** sequences by a **ground robot** GPS, Gyroscopes and Magnetometers, Lidars and Omni-directional camera. `http://3dvis.ri.cmu.edu/data-sets/localization/`
New College vision and laser [16]	**Outdoor** scenarios by a **ground robot** Stereo imagery captured (20Hz); 5-view omni-directional images (5Hz); range and intensity data from two lasers scanners (75Hz). `http://www.robots.ox.ac.uk/NewCollegeData/`
The Rawseeds Project	Bicocca (**indoor**) and Bovisa (**outdoor + mixed**) by a **ground robot** 12 ultrasound transducers; one IMU; multiple Cameras System; and multiple Laser Range Finders. **GT**: drawings and recovered robot trajectories with expensive LRF. `http://www.rawseeds.org/`
Victoria Park Sequence [11]	**Outdoor** environment with trees by a **ground robot**. Laser; GPS; and steering and speed of a ground vehicle. `http://www-personal.acfr.usyd.edu.au/nebot/victoria_park.htm`

Malaga Dataset 2009 [4] & 2013 [5]	**Outdoor** urban scenario by a **ground robot**.
	One stereo camera, IMU and five laser scanners. **GT**: by a set of three expensive Real Time Kinematics (RTK) GPS receivers.
	`http://www.mrpt.org/Paper:Malaga_Dataset_2009/`
	`http://www.mrpt.org/MalagaUrbanDataset/`

Ford Campus & North Campus Vision and LIDAR	**Outdoors** by a **ground robot** with loop closures.
	Two IMU, a 3D-lidar scanner, two 2D lidars, and an omnidirectional camera system
	`http://robots.engin.umich.edu/SoftwareData/Ford`
	`http://robots.engin.umich.edu/SoftwareData/NCLT`

KITTI [9]	**Outdoors** by a **ground robot** in rural areas and on highways two Grayscale cameras; two Color cameras; GPS/IMU; one 3D Laserscanner `http://www.cvlibs.net/datasets/kitti/`

[1] GT = Ground Truth.
[2] Other available datasets: `http://projects.asl.ethz.ch/datasets/doku.php?id=home`
`http://projects.asl.ethz.ch/datasets/doku.php?id=related_links`
`http://its.acfr.usyd.edu.au/datasets/`

Table 1. The well-known datasets for the research on Multi Sensor Fusion for Robotics

4 Multi Sensor Fusion Datasets

As the second contribution of the paper, several datasets have been recorded and made public to the scientific community interested on low-cost multi sensor fusion with 6 DOF movements. The datasets are intended to be a reference for all Multi Sensor Fusion works, allowing to test all the developed algorithms under the same conditions to compare them in an objective way. The datasets can be downloaded following this link: `http://vision4uav.eu/?q=dataimage`. To reach all research interests, the authors promise to do their best to record new more datasets if required by the scientific community.

The datasets have been recorded in two different formats: a ROS bag[12] that eases the reading of the data using ROS; and a custom log plus images that eases the data analysis. In addition to the timestamped sensor measurements, the datasets provide all available sensor parameters and calibrations.

The datasets are classified based on the environment in: **indoor environments datasets** (Section 4.1), **outdoor environments datasets** (Section 4.2), and **datasets with transitions between indoors and outdoors environments** (Section 4.3).

The datasets have been recorded in the environment of the School of Industrial Engineering of the Technical University of Madrid (address: Calle Jose Gutierrez Abascal 6, 28006 Madrid (Spain)), see Figure 3. All the datasets always start with the FuSeOn board located on a planar surface will all the sensors acquiring correct measurements if signal is available. The IMUs have been previously calibrated to zero; the GPS sensors have had enough time to acquire satellites signal (if available); and the cameras and LIDAR have had enough time to be started. In addition, to ease the depth estimation with the RGB cameras, a calibrated ArUco visual marker [8] has been placed in front of the cameras. The FuSeOn board has been carried by a human operator during the tests, who is always away to the LIDAR measurements and the camera images.

Sensor failures have not been recorded, because they can be easily simulated by the datasets users. Only environment dependent sensor malfunctions are included, like RGB-D camera malfunctions in outdoor scenarios, or GPS sensors signal lost in indoor scenarios.

The proposed datasets do not include Ground Truth because the authors consider that high-precision measurements are still measurements that can be used as MSF algorithms inputs. Under the authors point of view, to compute the "Ground Truth" to test the performance of a developed algorithm, the only correct option is the comparison against other algorithms using a particular set of sensors measurements depending on the research interest of each dataset user.

4.1 Indoor Environments Datasets

In indoor environments, all the sensors are expected to have a correct operation, except the GPS sensors due to the lack of satellite signal.

Three different datasets have been acquired, with diverse objectives:

[12] `http://wiki.ros.org/rosbag`

(a) outdoors (b) outdoors-indoors (c) indoors-outdoors (d) indoors hall (e) indoors corridor

Fig. 3. Examples of the environments of the recorded datasets.

- **Short sequence**: The first sequence that must be used in the research of MSF algorithms. The FuSeOn board moves in a small area. Some challenging situations appear occasionally, like image occlusions or fast movements.
- **Long exploratory sequence**: A higher level dataset. It is a sequence with a long exploratory movement through small corridors and large halls. Some other challenging situations appear occasionally, like moving objects, image occlusions or fast movements.
- **Long and closed exploratory sequence**: The most challenging one. It combines a long exploratory movement with the pass through previously visited areas, called loop closure.

4.2 Outdoor Environments Datasets

Unlike indoor environments, outdoor ones, expects a malfunction of the RGB-D sensor due to the interference of the IR solar radiation with its projected pattern. However, GPS sensors are supposed to have enough satellite signal to give a correct measurement.

Similarly to indoor datasets, three different purposes datasets have been acquired: a **Short sequence**; a **Long exploratory sequence**; and a **Long and closed exploratory sequence** with similar challenges.

4.3 Transition between Indoor and Outdoor Environments Datasets

To lead the research on Multi Sensor Fusion to its top level, a combination of indoor and outdoor environment has to be tackled. Transitions between indoors and outdoors are complex because some sensors suddenly stop correctly working, while others start given new correct measurements. Acquired images are very different in terms of lighting. Outdoor environments are larger than indoors, and their obstacles have also bigger sizes and faster movements.

Two datasets have been acquired, depending on the transition: an **Indoors - Outdoors transition**, and an **Outdoors - Indoors transition**.

5 Conclusions and Future Work

In this paper, a low-cost testbed for the research on Multi Sensor Fusion for Robotics, called FuSeOn, has been presented. This testbed has a well studied design that ensures its portability, allowing a person to easily carry it everywhere to acquire data or to test his algorithms. In addition, the testboard design guarantee its modularity and versatility, promising a low maintenance, and the possibility to reconfigure it or to add it new features or sensors.

The second presented contribution is the comparison between the available datasets, demonstrating the need of a new collection of datasets for the research in MSF applied to low-cost and small-size Robotics. As the last contribution, these needed datasets have been acquired using the presented FuSeOn testbed. They include the measurements given by all the sensors mounted on the FuSeOn testbed, together with its calibration parameters. The datasets have been recorded in very different conditions, including indoor and outdoor scenarios, as well as, transitions between them; with an adequate number of light weight, small size and low cost sensor measurements; and with variated 6 DoF movements.

Both, the hardware design, and the software source code running on the testbed, as well as the recorded datasets, have been made public available for the use of the scientific community, as part of the authors belief on the Open Science concept. In addition, the authors take on a commitment of do their best to improve the recorded datasets, as well as the FuSeOn testbed, if requested by the scientific community.

There exist two main possibilities to continue with the work presented on this paper. The first one, is related with future improvements on the FuSeOn testbed or in the acquisition of new datasets. The FuSeOn testbed can be enhanced by adding more sensors like thermal cameras, or optical flow sensors. The size reduction of the FuSeOn board could open a whole world of applications like using it onboard UAVs, at the cost of loosing modularity and versatility. Additionally, improvements on sensors calibration and "Ground Truth" computation for comparison purposes are interesting future works. The second possibility is to apply the presented FuSeOn testbed on the research on Multi Sensor Fusion.

Acknowledgments. The authors would like to thank the Consejo Superior de Investigaciones Cientificas (CSIC) of Spain for the JAE-Predoctoral scholarships of one of the authors and their research stays, and the Spanish Ministry of Science MICYT DPI2014-60139-R for project funding. Special thanks to Angel Luis Martinez for manufacturing the FuSeOn board, and to Miriam Uzuriaga for testbed name suggestions.

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