2014 International Conference on Unmanned Aircraft Systems (ICUAS)
May 27-30, 2014. Orlando, FL, USA

Small Low-Cost Unmanned Aerial Vehicle System Identification: Brief Sensor Survey and Data Quality, Consistency Checking, and Reconstruction

Nathan V. Hoffer, Calvin Coopmans
AggieAir
Utah State University
Logan, Utah, 84322, USA
Email: nathan.hoffer@aggiemail.usu.edu
Email: c.r.coopmans@ieee.org

YangQuan Chen
Mechatronics, Embedded Systems
and Automation (MESA) Lab
ME/EECS, School of Engineering
University of California, Merced
Merced, California, 95343, USA
Email: yqchen@ieee.org

R. Rees Fullmer
Dept. of Mechanical
and Aerospace Engineering
Utah State University
Logan, Utah, 84322, USA
Email: rrfullmer@usu.edu

Abstract—**This paper serves as the next chapter in a series of papers on system identification (system ID) for small low-cost unmanned aerial vehicles (UAVs). The purpose of this paper is to answer the question of, what is the next step in the process of system ID once a method of system ID and a model type have been selected? The focus of this paper is to show how sensors, data quality, and data consistency and reconstruction techniques provide an answer to this question. The paper also provides a broader scope for utilizing data consistency and reconstruction in small low-cost UAVs and how it can increase mission assurance and fault tolerance. A brief survey of small low-cost Micro-Electro-Mechanical systems (MEMS) sensors used in UAVs is given. Included in the survey is the data types provided by each sensor and issues of each sensor from a system ID perspective. The process of determining and improving data quality, utilizing data consistency checking and reconstruction techniques is outlined. The paper concludes with guidelines and lessons learned about sensor data for system ID and a future research direction.**

I. INTRODUCTION

Small low-cost unmanned aerial vehicles (UAVs) are a newly emerging resource for personal remote sensing for scientific research and civilian application. There are several obstacles that must be overcome before UAVs can be successfully integrated into civilian airspace. Of these obstacles the most pressing deal with safety such as obstacle avoidance, communication between manned and unmanned aircraft, and robust and fault tolerant systems [1]–[3]. System identification (system ID) plays a key roll in making UAVs more robust and fault tolerant. Models of UAV dynamics can be determined through system ID. With accurate models, robust and fault tolerant controllers can be designed, simulated, and evaluated. Thus system ID is a valuable tool in increasing the safety and robustness of UAVs.

There are several challenges when performing system ID on small low-cost UAVs. Often less than perfect sensors must be used due to size and cost constraints. Though low-cost sensors are not ideal for system ID, it is still possible to resolve a dynamic model of a UAV if care is taken to understand the issues associated with each sensor. Evaluating the sensor data quality and using data consistency checking and reconstruction can overcome many of the short comings of low-cost sensors.

This paper is the next chapter in a series of papers on system ID [4], [5] for small low-cost UAVs. The main contribution of this paper is to answers the question of what is the next step in the system ID process once a method of system ID and a model type have been chosen? Once a method of system ID has been selected the next step is to select sensors that will provide the required data and to asses the sensor data quality. The evaluation of the quality of sensor data ensures that system ID is possible with the selected sensors. This paper reviews several types of sensors with their characteristics relative to system ID of small low-cost UAVs. A process of assessing data quality is given. This process utilizes data consistency checking and reconstruction.

This paper is organized as follows. The correlation between system ID and the Architecture for Ethical Remote Infromation Sensing is discussed in Sec. II. This correlation emphasizes the importance of small low-cost UAV system ID. A brief survey of different types of low-cost Micro-Electro-Mechanical systems (MEMS) sensors is given in Sec. III with emphasis on application to system ID. Section IV defines the goodness or quality of data for system ID. Data consistency checking and reconstruction are presented in Sec. V. Finally concluding remarks with guideline and lessons learned and future work are given.

II. SYSTEM ID AND CIVILIAN SMALL UAS ARCHITECTURE

In a small unmanned aerial system (UAS) designed for remote scientific information gathering, the Architecture for Ethical Remote Information Sensing (AERIS) gives structure for systems where data is the mission (more details in [6] and in Fig. 1). In AERIS, navigation sensors and system ID are of high importance even with small low-cost UASs which are not traditionally subjected to system ID. The three main aspects of AERIS-compliance are:

1) Airspace Management for Safety: Airworthiness (airframe and operational equipment reliability), crew training, and certification, as well as policies and regulations to allow data collection missions.
2) Data Mission Success ("Dataworthiness"): The ability to capture quality remotely sensed data and to have the knowledge of the data quality, thereby providing data mission quality (DMQ) and data mission assurance (DMA) as metrics of mission performance.
3) Ethics: Privacy by Design: As in Cavoukian [7], privacy should be designed in to a system, whether by technical implementation (no-fly location databases) or by procedure (privacy protection training for operational crews).

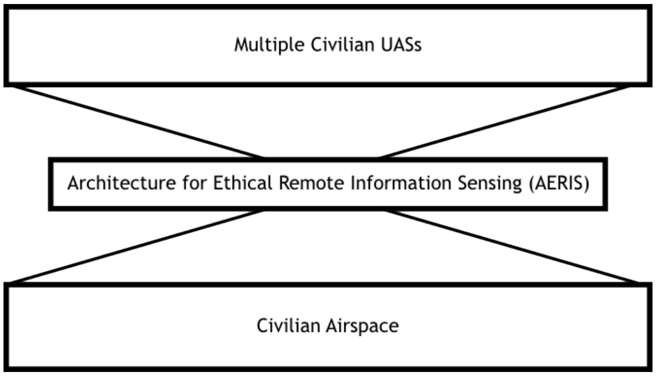

Fig. 1: An Architecture for Ethical Remote Information Sensing (AERIS) will allow remote sensing data missions in the civil airspace

Of the three aspects of AERIS-compliance, system ID is crucial for two; airspace management for safety and data mission success. The purpose of AERIS is to give an architecture that provides greater system robustness for safer and more reliable flight, as well as improving payload knowledge of flight characteristics for higher quality data. System ID plays a key roll in the development and flight of such UASs.

III. SENSORS

The selection of sensors is the next step in system ID once a method and model type have been chosen. It is important to evaluate the sensors prior to preforming system ID. This evaluation will prevent difficulties and ensure that system ID is possible with the given sensors suite. It is important to note that the selection of sensors has a direct impact on data quality, what variables are available for system ID, and what types of models are resolvable through system ID. This section deals exclusively with sensors that are suited for small low-cost UAVs which are generally MEMS.

There are two scenarios regarding sensors for system ID of UAVs. The first is a UAV has been constructed or purchased with sensors already in place and system ID is an afterthought. The second scenario is a UAV has been constructed or purchased and the sensors must be selected for system ID. In either case it is important to evaluate the sensor's outputs and performance to determine if system ID is possible with the selected sensors. It is also important to understand the role of sensors and sensor packages used for autonomous flight and how they correspond to system ID requirements. Understanding the requirements for system ID and autonomous flight could allow for the same set of sensors to be used for both applications. This is especially important when considering online system ID and adaptive control [8].

Historically sensors have been used in manned aircraft, spacecraft, and guided missiles. More recently low cost MEMS sensors have been implemented into UAVs making autonomous flight possible. Some sensors, particularly accelerometer, gyroscopes, and magnetometers are usually packaged into a single sensor housing. Three types of sensor packages used for autonomous flight will be discussed to give more insight into how these sensor packages can be utilized for system ID application and to point out when supplementary sensors are required. The three main sensor packages with their definitions are give in the following list:

1) Inertial Measurement Unit (IMU): reports velocities, orientation, and accelerations. Sensors in an IMU are accelerometers, gyroscopes, and sometimes magnetometers.
2) Attitude and Heading Reference System (AHRS): is a legacy term from manned aircraft that provides data to an artificial horizon and compass. For UAV applications AHRS provides heading, attitude, and yaw. AHRS uses accelerometer, gyroscopes, magnetometers and onboard processing to estimate the heading, attitude, and yaw.
3) Inertial Navigation System (INS): provides relative position, orientation, and velocity vector. An INS houses a computer, accelerometers, gyroscopes, or other motion sensors. The main purpose of an INS is to provide all necessary information for an unmanned vehicle to navigate without the aid of external references. Often INSs are supplemented with a GPS to reduce the accumulated error from integrating sensor data.

Many manufactures do not stay within the traditional definition of IMU, AHRS, and INS. Most sensors packages have some form of onboard filtering and are somewhere in between an AHRS and an INS. It is also important to understand what measurements are available from a sensor package. Some sensor packages only provide what is intended for autonomous flight and do not provide individual sensor measurements. Other sensor packages may filter the individual sensors to provide orientation but do not provided filtering on individual sensor measurements. Thus it is very important to understand

- How sensor data is processed
- How sensor data is calculated, if it is directly from a sensor or filtered and combined from several sensors
- What sensor data is available for logging

There are several possible sensors which can be used for system ID. The following list provide a basis of sensors actually used for system ID for small low-cost UAVs [5].

- Triaxis accelerometer
- Triaxis gyroscope
- Triaxis magnetometer
- Piezoresistive transducer absolute pressure sensor
- Piezoresistive transducer differential pressure sensor
- Laser altimeter
- Ultrasonic altimeter
- Global Positioning System (GPS)

A. *Triaxis Accelerometer*

A triaxis accelerometer measures linear acceleration in a body X, Y, and Z axis. Accelerometers have high frequency noise. Often power plant vibrations will show up in acceleration data. Mounting of the accelerometers should be at the center of mass. However this is not always possible since the payload is usually positioned at the center of mass for flight stability. Thus if the accelerometers are positioned some distance away from the center of mass then the accelerations must be compensated to account for the acceleration from rotation about the center of mass. There have been several studies detailing issues and solutions to MEMS accelerometers [9], [10]. MEMS accelerometers have long term drift which introduces biases into integrated velocity and position measurements. Accelerometer data must be processed to remove gravitational acceleration prior to system ID. Table I shows typical characteristics of accelerometers found in common IMUs.

B. *Triaxis Gyroscope*

Triaxis gyroscopes measure the rotational velocity around the X, Y, and Z body axis. They are susceptible to high frequency noise just as the accelerometers are. However gyroscopes are more prone to drift. Unlike the accelerometer measurements, the gyroscope measurements are not biased by its placement relative to the center of mass. Table I shows typical characteristics of gyroscopes found in common IMUs.

C. *Triaxis Magnetometer*

Triaxis magnetometer provides heading measurements and orientation. Due to the local variation in earth's magnetic field and the magnetometer's sensitivity, magnetometers are not primarily used for orientation. Generally they are used in a complementary fashion with accelerometers and gyroscopes for a more accurate orientation measurement. Table I shows typical characteristics of magnetometer found in common IMUs.

D. *Piezoresistive Transducer Absolute Pressure Sensor*

Low-cost absolute pressure sensors measure the air pressure and give the measurement as a voltage that must be converted into an actual pressure. The absolute pressure sensor can also be calibrated to give a measurement of altitude. The calibration must account for several factors since air density is a factor of altitude, temperature, and relative humidity. Table II shows typical characteristics of three absolute pressure sensors.

TABLE II: Comparison of piezoresistive transducer absolute pressure sensors

Specifications	Freescale Semiconductor MPXV7002GP [13]	Bosch Sensortec BMP085 [14]	Measurement Specialities MS5611-01BA03 [15]
Pressure range	$\pm 2kPa$	$30-110kPa$	$1-120kPa$
Accuracy	$\pm 2.5\% V_{FSS}$	$\pm 0.25kPa$	$\pm 0.15kPa$
Sensitivity	$1V/kPa$	–	–
Update rate	$20Hz$	$1Hz$	–

E. *Piezoresistive Transducer Differential Pressure Sensor*

Low-cost differential pressure sensors measure the difference in pressure and give the measurement as a voltage that must be converted into an actual pressure difference. The differential pressure sensor can also be calibrated to give a measurement of airspeed. The calibration must account for several factors since air density is a factor of altitude, temperature, and relative humidity. Table III shows typical characteristics of a differential pressure sensor.

TABLE III: Piezoresistive transducer differential pressure sensor characteristics

Specifications	Freescale Semiconductor MPXV7002DP [13]
Pressure range	$\pm 2kPa$
Accuracy	$\pm 2.5\% V_{FSS}$
Sensitivity	$1V/kPa$
Update rate	$20Hz$

F. *Laser Altimeter*

Laser altimeter measures relative altitude. Measurements can have sub meter precision and have hundreds of measurements per second. They are typically only used for low altitude hovering. Table IV shows typical characteristics of a laser altimeter.

TABLE IV: Laser altimeter characteristics

Specifications	Flir MLR 100 [16]
Range	$0-100m$
Resolution	$< 0.2m$
Update rate	$500Hz$

G. *Ultrasonic Altimeter*

Ultrasonic altimeters give relative measurements of altitude. They are limited to ground surfaces that have good acoustical reflective properties, such as concrete or grass. They are typically only used for low altitude hovering. Table V shows typical characteristics of a ultrasonic altimeter.

TABLE V: Ultrasonic altimeter characteristics

Specifications	MaxBotix MMB1240 [17]
Range	$20-765cm$
Resolution	$1cm$
Update rate	$10Hz$

TABLE I: Comparison of IMUs (accelerometers, gyroscopes, & magnetometers) from [11], [12]

Specifications	Microstrain 3DM-GX2	Microstrain 3DM-GX3	Xsens Mti-g (w. GPS)	ADIS16405	Ardu-IMU	VectorNAV VN-100
Orientation Accuracy (static)	±0.5° typical	±0.5° typical	$< 0.5°$(roll/pitch)	Only raw data	NA	$< 0.5°$ (roll/pitch)
(dynamic)	±2.0° typical	±2.0° typical	1° RMS	-	-	$< 2.0°$ typical
Update Rate	$< 100Hz$	$< 1000Hz$	$< 120Hz$	$< 330Hz$	$< 50Hz$	$< 200Hz$
Accel Bias	±0.005g	±0.005g	±0.002g	±0.05g(initial) 0.0002g(in-run)	N/A	±0.0005g(X,Y) ±0.0016g(Z)
Accel Range(default)	±5g	±5g	±50m/s^2	±18g	±3.6g	±2g
Accel Nonlinearity	0.2%	0.2%	0.2%	0.1%	0.3%	$< 0.5\%$
Gyro Bias (°/sec)	± 0.2	±0.2	1	±3(initial) 0.007 (in-run)	N/A	<0.028 (25°C)
Gyro Range(default)	±300°/sec	±300°/sec	±300°/sec	±300°/sec	±300°/sec	±500°/sec
Gyro Nonlinearity	0.2%	0.2%	0.1%	0.1%	1%	$< 1\%$
Gyro Random Walk Error	N/A	N/A	0.05°/sec/$\sqrt{}$Hz		N/A	N/A
Mag Bias (Gauss)	±0.01	±0.01	0.0001	±0.004	N/A	±0.000125
Mag Range (Gauss)	±2.5	±1.2	±0.75	±2.5	N/A	±6
Mag Nonlinearity	0.4%	0.4%	0.2%	0.5%	N/A	$< 1\%$

H. Global Positioning System (GPS)

A GPS module gives several different measurements and an estimation of the precision of those measurements. Typically a GPS provides a position in Earth Center Earth Fixed coordinate system that can be transformed in to a North East Down position. GPS also provides velocities and a heading. Table VI shows typical characteristics of two GPS modules.

TABLE VI: Comparison of GPS modules

Specifications	U-blox LEA-6H [18]	GlobalTop Tech Inc. FGPMMOPA6B [19]
Horizontal position accuracy	$2.5m$	$3m$
Velocity accuracy	$0.1m/s$	$0.1m/s$
Acceleration accuracy	$-$	$0.1m/s^2$
Heading accuracy	$0.5°$	$-$
Update rate	$4Hz$	$5Hz$

IV. DATA QUALITY

There are several metrics for determining the quality of data that a sensors provides. This section outlines what quality data is for system ID. When a sensor is used to control a dynamic system the quality of the sensor data must be evaluated. This is to determine if the data is of a sufficient quality for the controller to work as designed. Generally a sensor is evaluated based on measurement sensitive, frequency and types of error. These evaluation standards are only the beginning of determining the quality of data a sensor produces. So how should sensor data be evaluated to determine its quality? To answer this question one must first understand what the data is being used for.

In the case of autonomous flight one must understand what measurements are necessary. For a fixed wing aircraft, position and orientation are sufficient for basic navigation. Where as higher performance controllers may require position, orientation, aerodynamic angles, and velocity. Not only are different sensors required for different types of controllers but different controllers may require different levels of sensor accuracy. For example, a multirotor UAV performing an inspection of the underside of a bridge may require centimeter position accuracy. Where as a fixed-wing UAV designed to loiter while a camera operator follows an object of interest may only require meter position accuracy. Though autonomous flight controllers and system ID have many thing in common, this does not imply that the level of data quality needed for both is the same.

In an ideal experiment the data is noiseless, captures only the dynamics of interest, has no lag, is already in the correct coordinate system, and accurately represents the physical phenomena. This is not the case with real world flight data. There are several sources for error which can be divided into two categories: deterministic and nondeterministic or random errors. Common deterministic errors are:

- sign convention
- bias
- drift
- scale factor
- time shift

Examples of deterministic errors are presented in Fig. 2. Common non-deterministic errors are:

- data drop outs
- electrical noise
- vibrational noise
- air data disturbances
- quantization

Examples of nondeterministic errors are presented in Fig. 3.

V. DATA CONSISTENCY CHECKING AND RECONSTRUCTION

The previous section examined potential sources of error that occur in flight data. This section reviews the basic process of data consistency checking and reconstruction for UAVs. Data consistency checking evaluates the data set as a whole to detect and model errors [20]. This is done prior to system ID so that time is not waisted on attempting to resolve a consistent model from kinematically inconsistent sensor data. Data reconstruction techniques resolve the errors

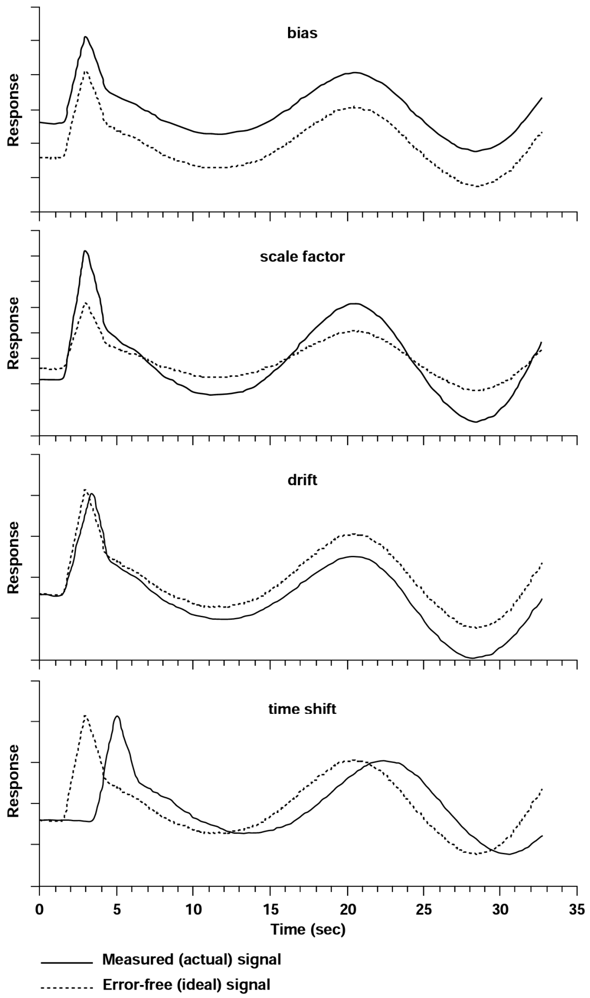

Fig. 2: Deterministic error from [20]

in the data, providing kinematically consistent data. The distinction between consistency checking and reconstruction is clear in theory. In practice the two blend together since in order to compare data from separate sensors, the data must be transformed into the same coordinate system. Thus data consistency checking and reconstruction happen some what simultaneously.

The process of data consistency checking consists of comparing different sensor data in the same frame of reference as well as using kinematic equations to compare data. This comparison is used to create a model of the sensor errors. Then the model can be used to reconstruct the actual data. Data consistency checking also includes an evaluation of filtering techniques to ensure that the actual dynamics are not lost. The process for data consistency checking and reconstruction is outlined as follows:

- Convert to consistent units
- Remove outlying data
- Filter noisy data
- Smooth data

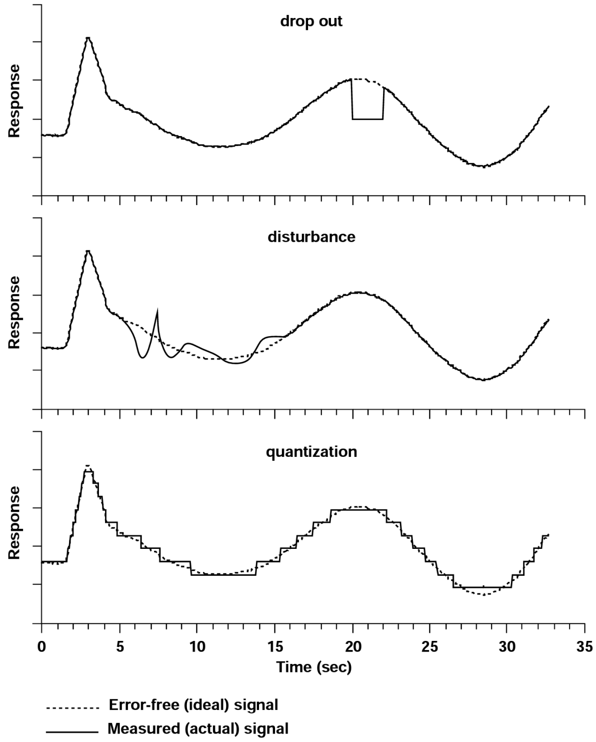

Fig. 3: Nondeterministic error from [20]

- Remove gravitational acceleration
- Transform to body coordinates
- Compare states and the change in state via integration and differentiation
- Use kinematic equations to compare measurements and the integrated change in states
- Create parametric model of sensor errors
- Reconstruct the error free signal using parametric model

Equation 1 from [20] is given as an example of a parametric model of the Euler roll angle Φ.

$$\Phi_m(t - \tau_\phi) = \lambda_\phi \Phi_e(t) + b_\phi + n_\phi \tag{1}$$

where the deterministic error are represented as b_ϕ is the bias, λ_ϕ is the scale factor, and τ_ϕ is the time shift. The parameter n_ϕ is modeled as zero-mean white noise and represents the nondeterministic errors

Each step of the process of data consistency checking and reconstruction will be discussed in further depth in a following journal paper due to space constraints. The next paper will give an example of data consistency checking and reconstruction of a fixed-wing UAV under longitudinal motion, and the issues and resolutions to identifying a dynamic model.

VI. CONCLUSION AND FUTURE WORK

A. Conclusion

This paper has presented part of the big picture of how a UAS can benefit from system ID both in development and during flight. A brief survey has been provided of low-cost sensors and their characteristics with regard to system ID. An over view of data consistency checking and reconstruction has been discussed. These sections make the next chapter of previous work done in system ID.

B. Future Work

The next chapter in this series of papers on system ID for small low-cost UAVs will continue with the example of data consistency checking and reconstruction of a fix-wing UAV under longitudinal motion. Also work on a method of identifying aerodynamic coefficients is under investigation. This system ID method will be implementable both on and off line and will serve as a basis for adaptive control.

ACKNOWLEDGEMENT

The authors would like to acknowledge Dr. Mac McKee of the Utah Water Research Laboratory. This work is supported by Utah Water Research Laboratory MLF 2006-2013.

REFERENCES

[1] "Integration of civil unmanned aircraft systems (UAS) in the national airspace system (NAS) roadmap," FAA, Tech. Rep., 2013.

[2] K. Dalamagkidis, K. Valavanis, and L. Piegl, "On unmanned aircraft systems issues, challenges and operational restrictions preventing integration into the national airspace system," *Progress in Aerospace Sciences*, vol. 44, no. 7-8, pp. 503–519, Oct. 2008.

[3] K. Dalamagkidis, K. P. Valavanis, and L. a. Piegl, "Current status and future perspectives for unmanned aircraft system operations in the US," *Journal of Intelligent and Robotic Systems*, vol. 52, no. 2, pp. 313–329, Feb. 2008.

[4] N. V. Hoffer, C. Coopmans, A. M. Jensen, and Y. Chen, "Small low-cost unmanned aerial vehicle system identification: a survey and categorization," in *International Conference on Unmanned Aircraft Systems*, 2013, pp. 897–904.

[5] ——, "A survey and categorization of small low-cost unmanned aerial vehicle system identification," *Journal of Intelligent & Robotic Systems*, vol. 74, no. 1-2, pp. 129–145, Oct. 2014.

[6] C. Coopmans, "Architectures for Cyber-Physical Enabled Ethical, Accurate, and Resilient Unmanned Aerial Personal Remote Sensing," in *Proc. of the 2014 International Conference on Unmanned Aircraft Systems (under review)*, Orlando, FL, 2014.

[7] A. Cavoukian, "Privacy by Design The 7 Foundational Principles Implementation and Mapping of Fair Information Practices," *Information and Privacy Commissioner of Ontario, Canada*, 2009.

[8] M. Samal, S. Anavatti, and M. Garratt, "Real-time neural network based identification of a rotary-wing UAV dynamics for autonomous flight," in *2009 IEEE International Conference on Industrial Technology*. Ieee, 2009.

[9] P. Li, W. Tianmiao, L. Jianhong, and W. Song, "An attitude estimate approach using MEMS sensors for small UAVs," *2006 4th IEEE International Conference on Industrial Informatics*, pp. 1113–1117, 2006.

[10] L. Sahawneh and M. A. Jarrah, "Development and calibration of low cost MEMS IMU for UAV applications," *2008 5th International Symposium on Mechatronics and Its Applications*, 2008.

[11] H. Chao, C. Coopmans, L. Di, and Y. Chen, "A comparative evaluation of low-cost IMUs for unmanned autonomous systems," *2010 IEEE Conference on Multisensor Fusion and Integration*, pp. 211–216, Sep. 2010.

[12] C. Coopmans, "Architecture , inertial navigation , and payload designs for low-cost unmanned aerial vehicle-based personal remote sensing," Master's thesis, Utah State University, 2010.

[13] Freescale Semiconductor, "Integrated silicon pressure sensor on-chip signal conditioned, temperature compensated and calibrated," pp. 1–11, 2009. [Online]. Available: http://www.freescale.com/files/sensors/doc/data_sheet/MPXV7002.pdf

[14] Bosch Sensortec, "BMP085 specifications," 2014. [Online]. Available: https://www.bosch-sensortec.com/en/homepage/products_3/environmental_sensors_1/bmp085_1/bmp085

[15] Measurement Specialties, "MS5611-01BA03 barometric pressure sensor , with stainless steel cap," pp. 1–20, 2012. [Online]. Available: http://www.meas-spec.com/downloads/MS5611-01BA03.pdf

[16] Flir, "Miniature laser rangefinder/altimeter," 2012. [Online]. Available: http://www.flir.com/cvs/cores/view/?id=56598

[17] MaxBotix Inc., "XL-MaxSonar - EZ Series," 2012. [Online]. Available: http://www.maxbotix.com/documents/XL-MaxSonar-EZ_Datasheet.pdf

[18] U-blox, "LEA-6 u-lox 6 GPS modules data sheet," p. 26, 2013. [Online]. Available: http://www.u-blox.com/en/gps-modules/pvt-modules/previous-generations/lea-6-family.html

[19] GlobalTop Tech Inc., "FGPMMOPA6B datasheet," pp. 1–29, 2007. [Online]. Available: http://anceop.com/?action=page&param=viewProduct&id=14082

[20] M. B. Tischler and R. K. Remple, *Aircraft and rotorcraft system identification: engineering methods with flight test examples*. Virginia: AIAA, Inc., 2006.