An Attitude Heading and Reference System: Basic Concepts and Prototype

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***Abstract*—This article proposes a basic platform for inertial measurements. In order to control an autonomous vehicle, it is fundamentally important to know its attitude. For aerial vehicles, this information is critical to determining the control loop's feedback parameters. For manned aircraft, roll, pitch and yaw can be obtained through orientation by an inertial reference, usually the ground, or instruments such as an artificial horizon or a compass. Still all of them are dependent on pilot interaction. For unmanned platforms, it becomes necessary to use an electronic device capable of measuring physical quantities related to that goal. A device that aggregates these sensors is called IMU (Inertial Measurement Unit). An IMU contains inertial sensors that measure linear acceleration and angular rate, among other physical data. Through reading and fusing these data it is possible to obtain attitude information which, applied to flight history, can help to determine the position relative to an initial position, as well as feeding the control loop with the necessary data to control actuators, in a way that allows an aircraft to be stabilized or maneuvered to follow a predetermined trajectory, fulfilling the role of replacing a pilot. Our proposed platform is composed of sensors for inertial measurements, as well as a basic firmware capable of estimating the attitude of the platform, effectively creating an attitude heading reference system (AHRS).**

I. Introduction

In order to perform autonomous navigation, it is necessary for the researchers to be aware about the current state of the system, even before taking into account the destination itself. One way to acquire information about this state is through various sensors that are able to take measurements about the motions of the system. Other complementary information may be obtained from non-critical devices, such as, for instance, a Global Positioning System (GPS)[1][2] receiver. That despite being susceptible to limitations of a system based on satellite communications, it can be used as a secondary reference input. Another option is a barometer, which, through measures of atmospheric pressure, helps the system to find its altitude in relation to sea level.

In the context of this project, sensors are used to determine attitude of an object. More specifically, the developed platform can be used to discover yaw, pitch and roll of UAVs (Unmanned Aerial Vehicles). This is the main role of an AHRS, or Attitude Heading and Reference System. From the information gathered by this sensor and the mechanical model of the aircraft, one can find the parameters needed to establish and maintain an automatic flight control - a major step to build an autopilot.

In the proposed research prototype, commercially available MEMS (Microelectromechanical Systems) sensors are used. These sensors, although less accurate than the normally used in military and civilian aircrafts, are able to meet the requirements for the construction of a small or medium-range UAV.

II. Estimating the Attitude

Ideally, it might be possible to determine the orientation of a still object through only three sensor measurements (referring to three degrees of freedom - DOF). However, there are no single sensors that can provide the direct measurement of orientation, simply because orientation itself is a relative concept. Even though, the measurements might be affected by factors such as noise - common for all electronics circuits. Besides, for a moving object with variable acceleration in an unbounded environment, these measures may be dependent on frequency and other effects, and problems could arise from coupling between channels. Even human sensory mechanism can be fooled by wrong input, and that is the reason why fighter jet pilots must be specially over trained for such situations.

Nevertheless, modern systems typically use a microprocessor for this task. Digital characteristic for this equipment allows many improvements in algorithms, specially in terms of flexibility. However, when using digital devices, other factors may arise which affect the accuracy of the information, such as sampling jitter, numerical and quantization errors. Furthermore, fast control loops are required for adequate operation of the algorithms.

Implementing the complete system needed to an AHRS may be very complex. For the sake of simplification, this research was divided in 3 (three) main stages: hardware, firmware and software. These three research subjects, although different in concept, were developed in parallel during the project, because of their interdependence and the need to feed data from one component to the others.

The goal of this project is to develop a basic platform capable of acquiring the data made available by some low-cost inertial sensors with no further regards about accuracy. Then, the embedded micro-controller fuses this information to determine platform attitude. Then, this project aims to create a basic environment for the development of new, improved

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algorithms, and a natural application is, for instance, an autopilot.

This platform might be modular and scalable, allowing it to be used not only in fixed-wing aircraft, but also in other remotely operated vehicles, airborne or not, and independent devices, like image stabilizers and navigation equipment for locations where GPS is unavailable.

A. The Hardware Scenery

Inertial sensors such as accelerometers, gyrometers and magnetometers are the main components of our platform. Information from these sensors is read by a microcontroller through either digital or analog means. This microcontroller then performs data fusion and sends the information to a computer through one of its multiple serial interfaces.

An accelerometer is fixed in the vehicle. The accelerometer measures its own acceleration. In the sensor, because there is only one output per axis, all accelerations, including gravity, are added. For our purposes, measured acceleration (a_m) might be composed of dynamic acceleration (a_d) and gravitational acceleration (g) (1).

$$\vec{a}_m = \vec{a}_d + \vec{g} \tag{1}$$

Therefore, we might calculate these two components from Eq.(1). One solution is to ensure that the dynamic acceleration of the platform becomes null by holding it still, remaining only acceleration of gravity. However, to hold still the object defeats the purpose of a mobile platform. Nevertheless, this principle can be applied by exploring frequency properties of the signal. For this purpose, a low-pass filter can be used to determine the components of gravity for objects with no continuous dynamic acceleration. With gravity vector, it is possible to determine part of the sensor's orientation, except for the angle around this same vector. This becomes the first component of the inertial measurement. Also, with a high-pass filter, or just subtracting the gravity from the measured vector, we get $\vec{a}_d = \vec{a}_m - \vec{g}$, which is, after all, dynamic acceleration. This process is illustrated in Fig. 1. This vector can be used in an Inertial Navigation System to get the platform's position, through double integration in a process called dead-reckoning.

A gyrometer is a device similar to a gyroscope. However, while the former measures angular variation of its axis ($\dot{\theta}_g(t)$), the later directly measures its orientation against a fixed reference point ($\theta(t)$). With this data, one must first integrate its value to obtain orientation in relation to an initial state (θ_0) (2).

$$\theta(t) = \int_0^t \dot{\theta}_g(t)dt + \theta_0 \tag{2}$$

Due to current MEMS technology and the need for numerical integration, this type of sensor is less precise than aviation-grade gyroscopes. However, MEMS sensors are much cheaper. Also, since several of these devices are fabricated from vibrating elements MEMS technology, they are also lighter, smaller, more durable and can be easily integrated to microelectronic circuitry. Those characteristics make them usable in smaller UAVs, where low cost and light weight are main concerns.

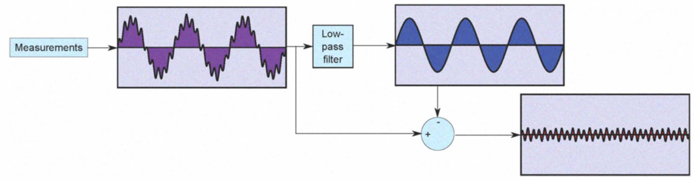

Fig. 1. The process used to estimate the gravity from the accelerometer measurements. After the measurements are made, the values are passed through a low-pass filter to estimate the gravity components. The rest should be the higher frequencies, which compose most of the dynamic acceleration.

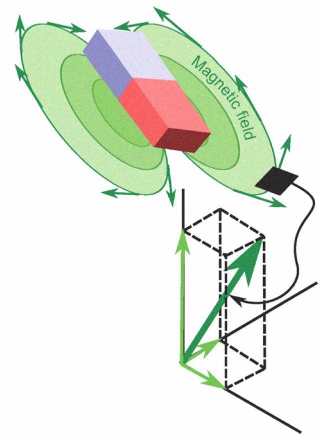

Fig. 2. A magnetometer measures the magnetic field vector in its location.

A three-axis gyro complements the accelerometer by providing desired angular information at higher frequencies, which is needed to stabilize an UAV moving at high speed. However, due to the drift effect in gyroscopes, due to noise and integration errors, a correction still needs to be done through an additional sensor.

A magnetometer is the sensor used for this purpose. This is a device capable of measuring surrounding magnetic field (Fig. 2). There are several types of magnetometers, built for usage in various applications, from Hall effect sensors to count gear teeth to sensors for magnetic resonance imaging (MRI) medical equipment.

For this project, it was used a magnetometer capable of measuring the three axis of the magnetic field strength vector $\vec{B}_{3\times1}$. This vector is used to correct the drift not only in the Z axis, but also aids the correction of the other ones, through a control loop.

The information from all those sensors must be read through either digital or analog interfaces and finally the data must be processed. All of this is done through a microcontroller executing a data fusion algorithm, sampling each analog sensor at a rate of approximately 50000 samples per second, with a 12-bit analog-to-digital converter. The microcontroller also passes the received values through a software low-pass filter, to complement the external passive filter and reduce noise. The chip used for this task was carefully chosen to have enough processing capacity not only for the operation of reading the sensors and making the attitude estimation, but also enough for the future expansion of the platform, turning it into a complete autopilot for the IME's UAV. Thus, we used a 72 MHz microcontroller, Cortex-M3, ARM architecture (32 bit). The chosen microcontroller has all the peripherals needed to read both the analog and digital sensors, and various serial interfaces which allow communication with expansion peripherals or computers.

Among the externally connected devices is a SecureDigital card to perform data storage during a test flight or mission, allowing posterior analysis.

The printed circuit board layout is shown on Fig. 3. The layout was designed to allow for manufacturing using a single copper layer, with minimum external connections. This was done to simplify prototyping during the experimental phase, allowing for corrections without the need for building another board.

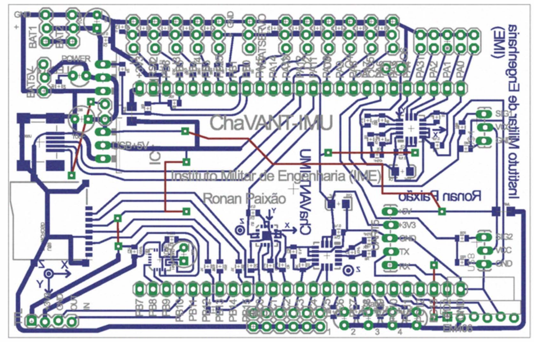

Fig. 3. Layout of the circuit board.

B. Firmware

Firmware is the program which runs inside a microcontroller, along with its data structures. This application is stored in the chip's internal flash memory.

Since our developed program is quite complex and requires fast operation, C/C++ [3] programming language is used. The language is easily portable, a feature that is also appreciated as it allows for expansion to other microcontrollers, if necessary, by just rewriting the device-dependent code.

Careful use of a hardware abstraction layer library may provide further help without compromising too much performance. Such a library was provided by the chip's manufacturer, and it follows the CMSIS standard [4]. This standard was created by ARM Holdings itself to facilitate the deployment of software for microcontrollers based on its Cortex-M platform, organizing definitions of names, register addresses and auxiliary functions to access the main features and peripherals. It also defines a device-independent interface for real-time operating systems' kernel debuggers.

After acquiring data from three main inertial sensors, the microcontroller iterates through the attitude estimation algorithm. The used algorithm is derived from sf9domahrs project[5], with many modifications to suit the peculiarities of the new hardware, which is quite different from original. That algorithm, by its turn, was developed from modifications to the design of William Premerlani [6], which is based on ideas from [7], [8], [9] and [10]. Besides, it can be exchanged with other algorithms, which allows researchers to experiment and compare their performances.

With sensor data, the algorithm updates a matrix called Direction Cosine Matrix, or DCM. This matrix represents any rotations (in this case the orientation of a vector) through a $\mathbb{R}^{3\times 3}$ matrix. Furthermore, it has no singularities, which, similarly to the quaternion, makes it an interesting way to represent rotations without stability problems. However, despite the quaternion representation also being viable and having even fewer values to be stored (only 4, while the DCM has 9), the DCM simplifies projection operations that is useful for the future control of the aircraft.

With the DCM updated, it must be orthonormalized. This operation forces the matrix to remain orthogonal and its normal to remain equal to unity. The fact that each new measurement, taken from independent axis, makes changes in the orthogonality of the matrix allows the algorithm to determine part of the noise from the sensors. With orthogonalization and renormalization, some of this noise is attenuated and the DCM remains stable.

With the DCM renormalized only from the accelerometers and gyros, another operation may be applied to avoid sensor drift. In this new procedure, the magnetometer provides more data to correct this problem through a control loop, making the information generated by the algorithm more precise.

In the end, Euler angles may be calculated from the elements of the DCM matrix. Thus, this results in the well known values of pitch, roll and yaw.

C. Software

In order to allow the research of some characteristics of the system, a desktop computer software was developed (Fig. 4), aimed not only at meeting the needs of visualization for the data generated by the inertial measurement unit, but also as a starting point for a command and control system for remotely operated vehicles. Therefore, it incorporates many features useful to the operation of an unmanned aircraft.

The software is capable of displaying maps or aerial photographs, overlaid with icons to indicate the positions of interest, particularly UAV and its base of operation. The software also has graphs to visualize the measured data, a display with a three-dimensional (3D) representation of the aircraft's attitude (Fig. 5), an artificial horizon (Fig. 6), and it has resources to perform automatic antenna tracking.

During hardware construction, software requirements are necessary for the correct visualization of measured data, since commercial systems which were available to the project team at the time were incapable of displaying such a number of graphs in real time.

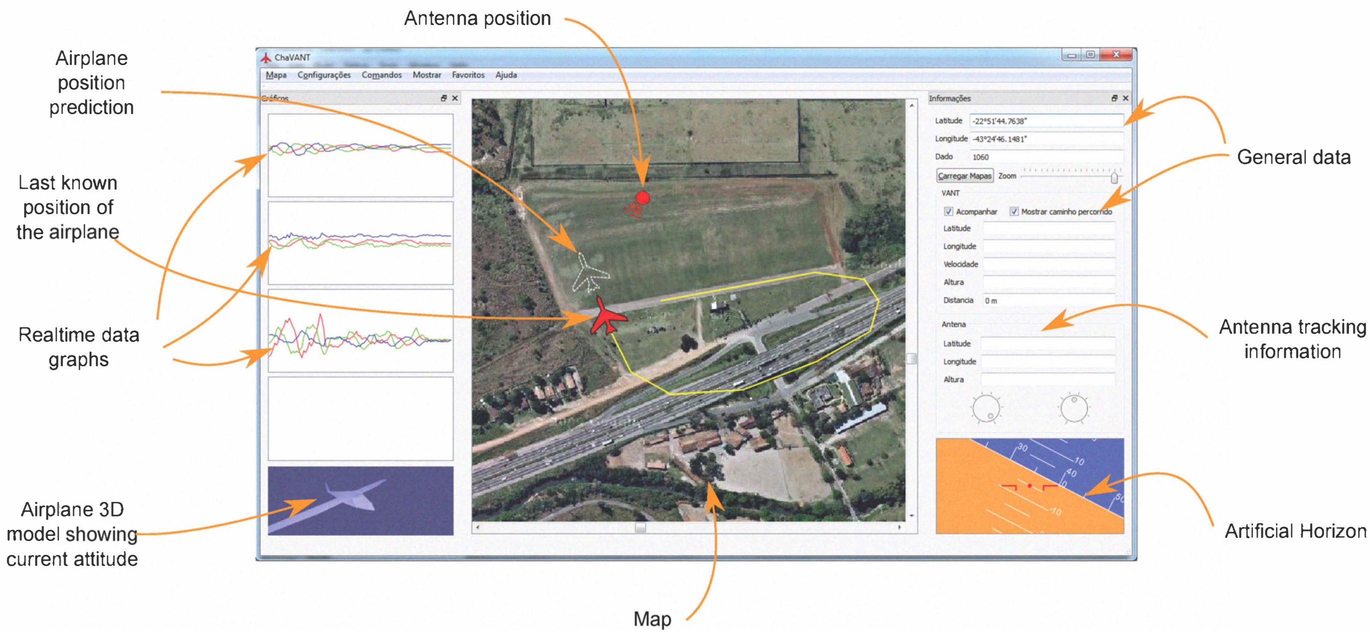

Fig. 4. Main screen of the developed software with its main features.

III. Experimental Results

With all software parts of the system ready and the hardware tested, the experimentation phase began. During this phase, the data was transmitted by a serial data port (UART1 in the microcontroller) connected to a computer through a USB-serial cable. This setup used only cables for transmission, to achieve fast data rates and higher reliability while the system was not used in a mobile platform.

For these experiments, the circuit was powered by the USB cable, which provided 5 volts. This voltage was then converted to 3.3 volts needed to operate the system through an on-board regulator.

In order to verify the performance of the attitude estimation algorithm executing inside the microcontroller, several different measurements were made, which stimulated each sensor individually. These measurements, as well as the output of the attitude estimation algorithm, can be seen in graphs of Fig. 7. The visual comparison between the measurement device and the 3D representation of the vehicle in the computer, as well as the artificial horizon for that particular attitude, is shown in Fig. 8.

Finally, the system was composed of a printed circuit board that incorporates all the necessary electronics for monitoring and processing the data provided by the digital and analog sensors. Associated with the microcontroller board, a firmware capable of meeting the basic needs of our UAV project was developed[11]. Also, a software was created for the analysis and visualization of the measured and generated data in a computer.

IV. Conclusion

The proposed device is able to perform measurements of linear acceleration, angular velocity and magnetic field; besides, it can process this data and generate information that indicates its own orientation. Finally, this data, including the raw measurements, was stored on embedded media and transmitted to a computer to allow visualization in real time, thus achieving the project's objective.

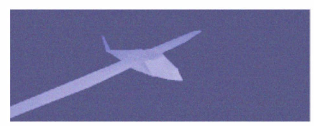

Fig. 5. 3D model visualization available in desktop application.

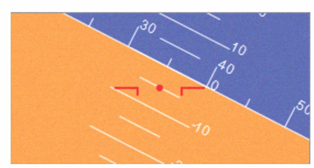

Fig. 6. The artificial horizon widget.

This is the basic research, development and prototyping for a basic inertial navigation system, including the production of printed circuit boards with electronic sensors and a micro-processor, as well as the embedded programming needed to integrate them. This device is the basis for future studies in the field of inertial navigation in our laboratory.

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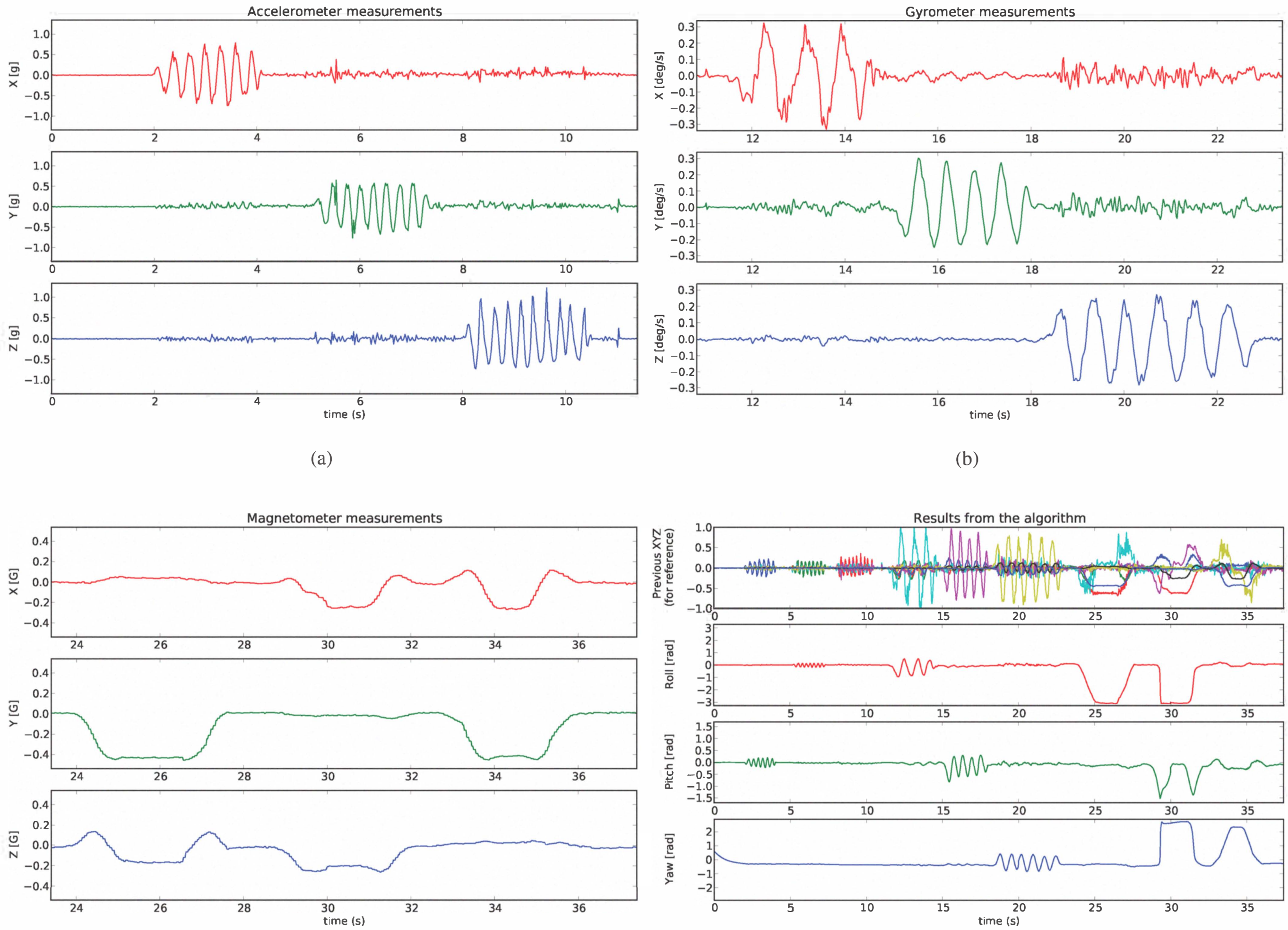

(a) (b) (c) (d)

Fig. 7. Graphs generated in the experiment: (a) the accelerometer measurements, (b) measurements from the gyros, (c) measurements from the magnetometer, and (d) all the measurements gathered and calculated attitude (roll, pitch and yaw).

that allowed this project.

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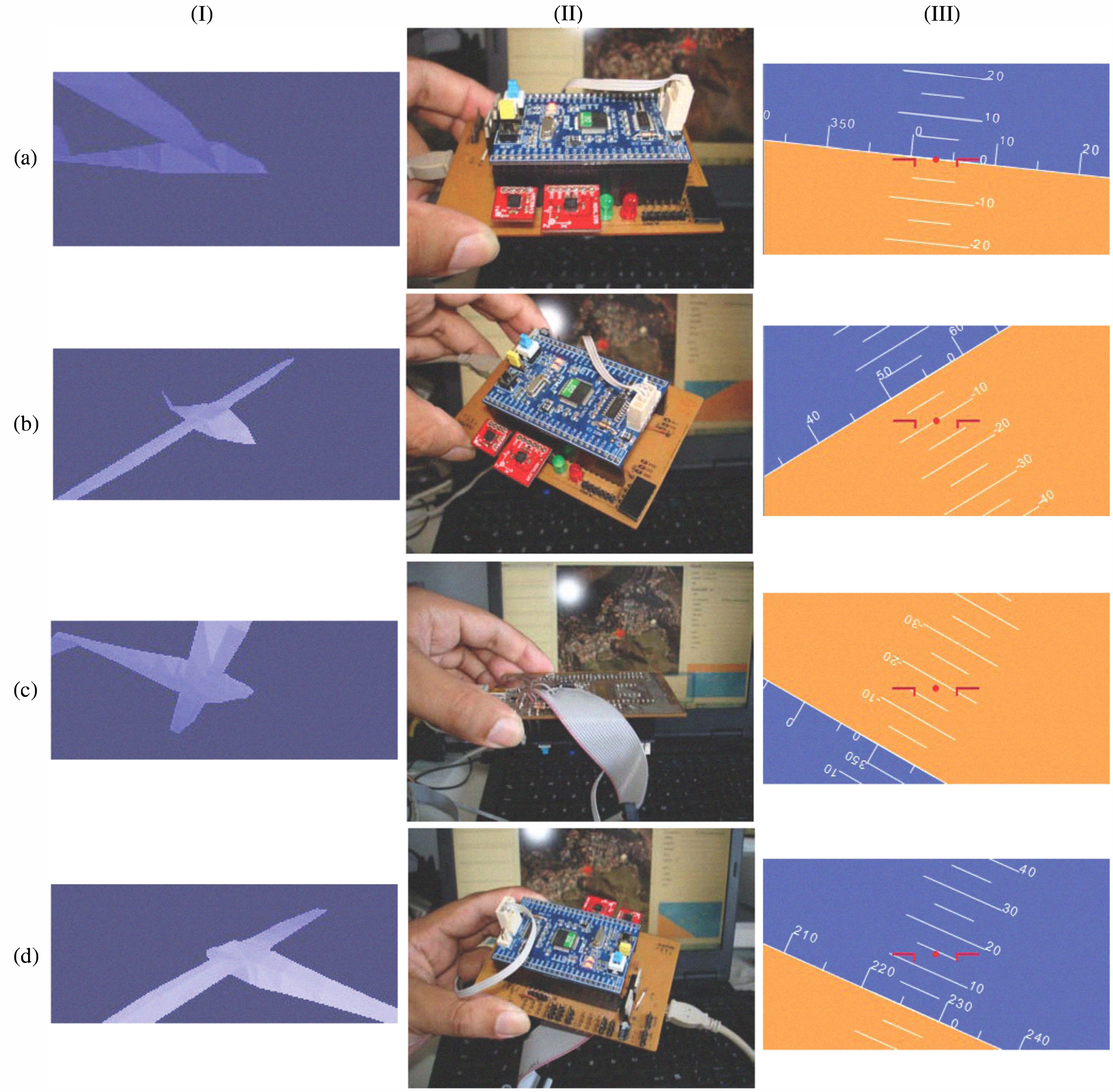

Fig. 8. Real-time simulation. In column (I), object attitude, in (II) AHRS manipulation, and in (III) artificial horizon. In row (a) a cruising flight, in (b) right down inclination, in (c), upside down, and in (d), left down inclination.