Head Tracking based on accelerometer sensors

CarloAlberto Avizzano, Patrizio Sorace, Damaso Checcacci*, Massimo Bergamasco
PERCRO, Scuola Superiore S.Anna
P.zza dei Martiti 33,
Pisa, 56100 (ITALY)
E-mail carlo@sssup.it

Abstract

The present paper presents a novel user interface for navigation in virtual environments and remote control of devices. The system proposed is head-mounted allowing for the control of up to six degree of freedom while keeping hands free.
The device is composed of six linear accelerometers arranged on a couple of glasses and a specific embedded controller that allows for the measuring of glass acceleration information. This is then translated in motion control information for navigation in virtual environments and/or as other devices input.

1 Introduction

Head tracking has been especailly investigated since early nineties, when immersive Virtual Reality technologies required for the tracking of the head position, that was essential to identify the perspective view of the user and consequently draw out the correct scene within the virtual environment [1].
Three different kinds of technologies, reported within the references, have already been employed for these purposes: optoelectronic sensors [2], acoustic sensors [3] and magnetic sensors [4]. At present the trackers most widely used employ magnetic sensors. This was due both for cost and practical factors: such sensors have the advantage of being small, unobtrusive and, with respect to the classical optical trackers, they do not suffer of visual and workspace limitation. Nonetheless these models usually present great latencies and suffer the interference of other magnetic fields and/or metal pieces. The present state of the art in the research related to these device, results in high encumbrance, high cost commercial solutions which strongly reduces the fields of application.
Conversely, the role of this kind of devices can be noteworthy in several kind of Virtual-Reality based application such as telesurgery [5], Simulators [6], teaching, games, art, tele-manipulation and CAD design [7]. The added value to be able in controlling the user point of view with natural movements of the head, greatly benefit the kind of interaction in these applications.

Several devices have been developed and commercialized on the market: the most well known are the Intersense products which allow for measurement of head position in rooms as large as 30mt. Magnetic sensors were provided for use in well conditioned spaces by Polhemus and Ascent and allow the accurate measurement of several sensors at once. The Virtual Track (http://www.vrealities.com/virtuatrack.html) is a 3DOF (Roll, Pitch and Yaw) head mounted sensor which can be connected to Personal Computer (via the serial port) for interaction with VR games and applications. The operation of the system is achieved by measuring the ambient magnetic vector fields. The application interface allows the mouse emulation. TrackIR is a monitor mounted sensor which allows the detection of the head position. It should be used in conjunction with the ED glasses and it is typically employed for games such as flight simulators. The user is located just in front of the sensor.

In this paper a system for the reconstruction of the motion, based on inertial sensor inputs, is described. As commented by Verplank in [10], the error of this system is "multiplied by t^2", typically and induce "huge position errors: in just 60 seconds, a one-dimensional IMU using an accelerometer with an output noise level of just 0.004 g yields a position uncertainty of about 70 meters". The present paper will also show how, implementing some non-linear reconstruction algorithms, it will be possible to largely reduce such an error.

2 Description of the system

The layout of the developed prototype is shown in the following figures, three dual axes linear accelerometers have been placed on the external border of the glasses. Standard Analog Devices ADXL 202 sensors have been used for this pourpose. Such sensors were chosen in order to match with the typical acceleration encountered during motion while neglecting the resolution capabilities of the device. Such accelerometers are very small in size since

they employ MEMS technology to embed mechanical components and electronics in one chip. Typical resolution for these sensors was 3mg, while saturation was set in +-2g..
According the application notes, the accelerometers were configured with few electronic components in order to provide the acceleration information on a bandwidth of 500Hz. Each accelerometer has been placed on a different plane (XY, XZ, YZ) with the Z axis approximately parallel to the gravity vector.

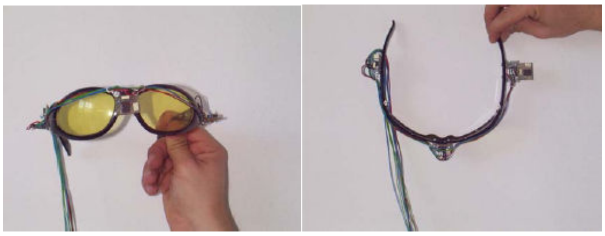

Figure 1: System prototype overview

The position and orientation of the accelerometers has been chosen in order to optimize the measurement of differential acceleration among two different accelerometers. This has been achieved by maximizing the axis-relative distance between the sensors measuring the acceleration oriented in the same direction. Distance between front and lateral sensors was typically 14cm, while distance between ears sensors was about 18cm (these values may vary according to way of wearing and user's head size).
The following picture shows the disposition of the sensors.; only the measured angles were outlined in frames.

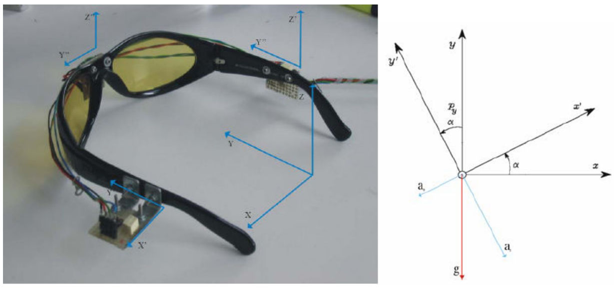

Figure 2: Axes orientation and initial calibration scheme

Once the system has been assembled, an initial calibration of the device was achieved by placing the device in predefined orientations (horizontal and vertical plane) and measuring the offset values given by sensors.
This procedure has allowed us to measure the misalignment of the sensor with respect to the vertical and horizontal plane, by using as source of information the direction of the gravity vector (measured by the sensors themselves).

2.1 Use of the system

Once the glasses have been put on the user has one control unit provided with few switches and buttons. The role of this unit is that of managing the whole interaction between the the glasses and the virtual environment. In fact, the unit is connected to the glasses and provides the remote communication with a serial connection to a PC. Such a design has been chosen in order to easily move from a cable connected solution to a radio one, which at once will solve the workspace and mobility limitation. The box also includes all required electronics to drive the remote sensors, acquire and elaborate the outputs in order to codify them into the required motion inputs. A specific serial motion protocol (on RS232) has then been implemented in order to connect the system to any kind of computer.

Figure 3: the handheld control and interaction unit and wearing calibration phase.

The size and the cabling connection of the unit have been chosen so that the unit can be held in the hand as well as stored in a pocket. The interaction with the unit is governed by few simple signals: operating mode, power, position reset and calibration. The buttons can also be used to provide more input for a remote application in case of necessity.
The operational diagram of the unit is defined by the following steps:

1) Wearing;
2) Wearing calibration;
3) Navigation mode selection;

4) Position Reset;
5) Navigation

The phases may be exchanged in order, still providing functional operation of the system (i.e. mode switch, calibration and reset may be issued at any time).
Two navigation modes are possible: rate navigation and positional navigation. In both cases the acceleration felt by sensors are used to “walk” within the virtual environment. In the first mode the head is used as a multidimensional Joystick to control the rate of motion in the VE, while, in the latter one, navigation is achieved by actually walking around.
Wearing calibration is similar to the initial calibration phase mentioned above, but it is used to compensate for the specific wearing errors induced by each user and, at once, the way he keeps the head during walking. Wearing calibration is done by asking the user to keep the head in normal position and to press the relative button.

3 Motion Detection Setup and Analysis

Before proceeding to the setup of the motion recognition software, some analyses have been performed on the motion signals, in order to identify which spectral and time features were dominating during motion. The whole motion signal were found not to have significant components over the 20Hz frequency, while typical accelerations were found within the +-3 m/s2 range.
Visual inspection of walking data also allowed to clearly distinguish between walking and orientation changes of the user's head.
Visual inspection for the design of the acceleration-noise washing filters were also a common practice in literature [8].
The above figures report the case of a simple walk: two steps ahead, two backwards, two ahead again. The image on the top is time history of the movement represented in m/s^2, while the relative Power Spectral Analysis of the same movement is represented below (DB vs Hz). These data were collected and used as part of a statistical analysis to identify the motion properties.
Using these data the two motion algorithms have been set up. The algorithms for the rate navigation mode, the initial calibration and the wearing calibration will be only briefly discussed in this paper. The rate navigation mode is relatively simple to be realized. The initial calibration has been determined by assuming that during calibration phases the measures along axes always reports components of the same acceleration vector arranged in well known differential orientations.

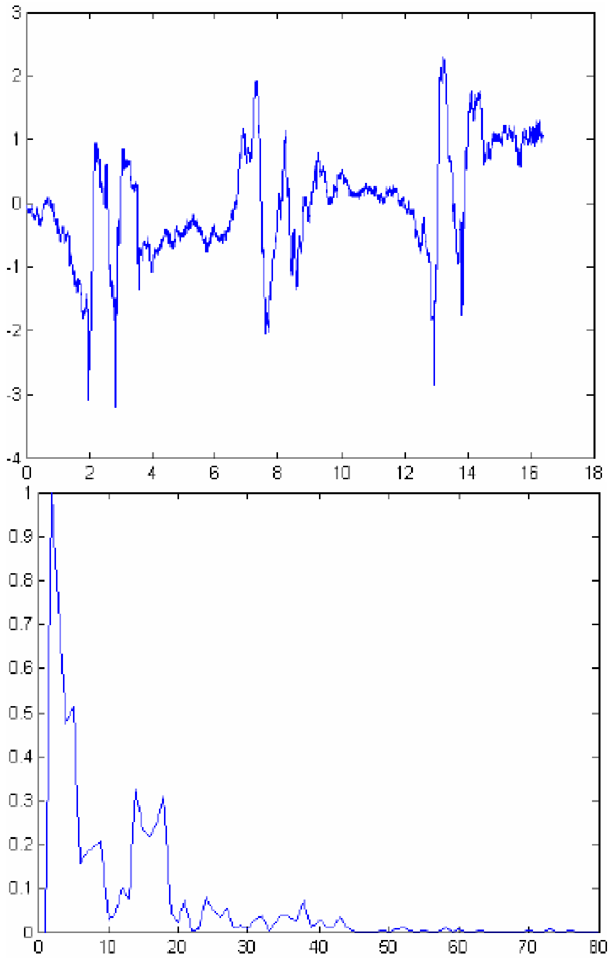

Figure 4: Double step sequences

It is a specific interest of this paper to show how motion integration algorithms have been set to work with planar integration (2D) and spatial movement detection.

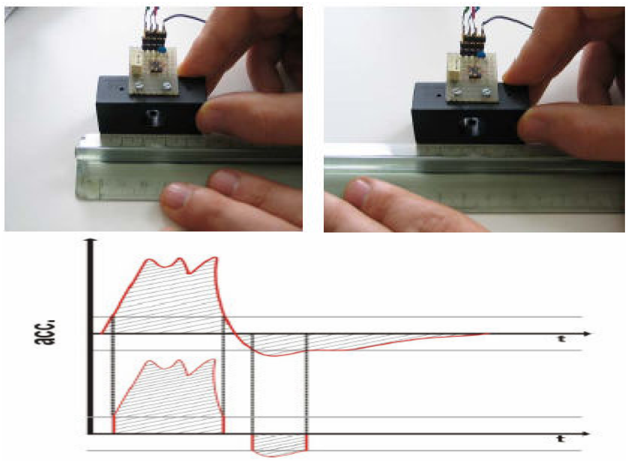

Figure 5: Linear Analysis method

The sensors were first arranged in a simple tracking way, as shown in figure 5. Several integration attempts were approached in order to find out which linear solution could be best suited to provide spatial motion measurements, but none was found to be properly working (low pass filter, kalman, optimal filtering,…). This was due both to several errors distributed in the system, as well as to the non-symmetric nature of the movement. According to initial investigation phase and the effective experiments done, the acceleration [11, 12] patterns differ according to the motion phase: acceleration vs deceleration; and direction: frontal/lateral, forward/backward. It is very difficult for any linear system to provide a double integration of the signal while rejecting errors which lead to drifting.

4 Integration Algorithm

The idea for providing a solution was that of setting up a non-linear system which, by looking to the signal information, decides what values actually identify a motion and which of them should be considered as errors. Furthermore the system measures were implicitly constrained to be related to a quasi-static system: a sensor which remains in the same region of the space. The setup of the non-linear filter was achieved by inspecting the properties of the motion signals during determined sequences of movement, and by identifying a proper structure for integrating only the meaningful data [13].

The basic principle of the non-linear integration is shown in the picture below: a dead zone has been first inserted in order to cancel noises collected by sensors. The threshold of the zone was experimentally determined by collected samples. Then a control logic, represented in the dashed box, identifies if the movement is persistent or not and resets the integrated velocity, whenever a prolonged under-threshold signal is identified. This structure was determined by examining what typically happens during motion paths. The movement is almost always characterized by a non-uniform velocity (acceleration is always present) except for the cases in which the user stops. It is almost impossible for the user to keep its speed exactly constant during motion leading the control logic to an error.

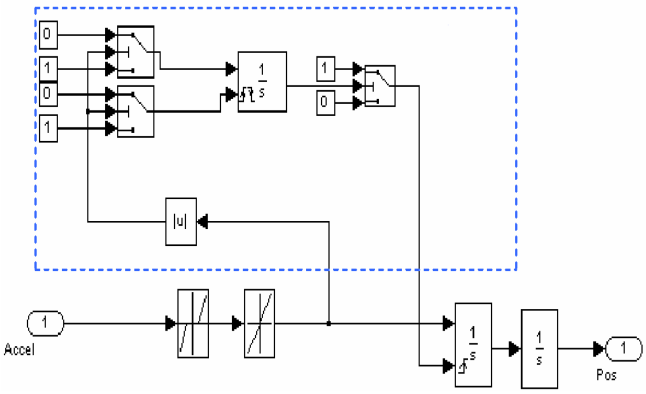

Figure 6: Basic integration scheme of the system

Several variations to the basic scheme have been tested to test if a combination of non-linear structures with linear and optimal filters could lead to better results. Noteworthy was a solution based on the separation of the spectral components.

Spatial navigation was complicated by orientation issues. It is very typical that during walking users change their head orientation even consistently for the sensors but without even noticing it. In the following picture it is represented the case of two steps ahead, two backwards (outlined with ellipses).

Between the forward and backward motions the user stopped for a couple of seconds. The differences in head orientation in these phases lead to a difference in measure of about 1m/s2 between the start and the end position. As a result it is impossible for the motion integration to distinguish which accelerations were caused by motion and which from head orientation change.

To solve this problem two algorithms have been set up.

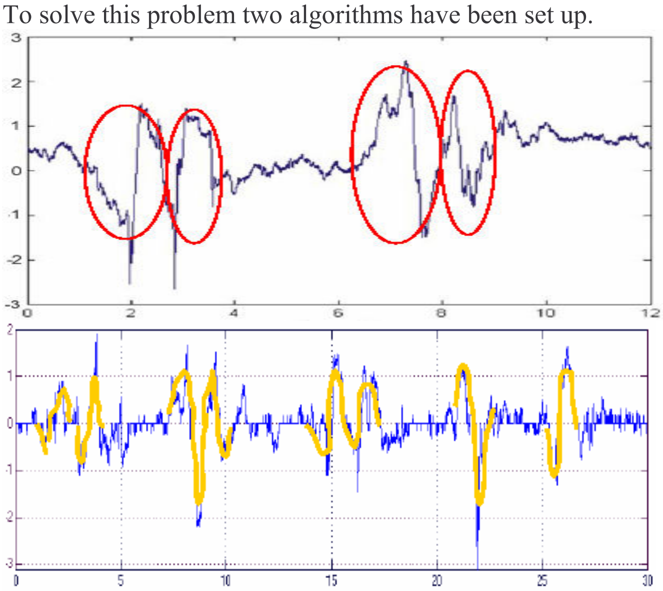

Figure 7: Acceleration and Band Pass filtered outputs

The first one was based on spectral separation of the component. Low pass and band pass signals were used to extract orientation and motion information, in a similar fashion to what described before Low pass information, was then continuously used to get a interactive orientation compensation in the integration algorithm. As a results motion integration was achieved but produced much higher errors than in the previous planar case.

Looking again to the signal data a different attempt to the motion reconstruction was provided. Such an approach is not base on the signal integration itself anymore, but on the whole signal analysis. Visual inspection easily shows the parts of the trajectories that were related to motion and those instead, that were due to change in head orientation. Typically any step is identified by a start (an acceleration

phase, followed by a deceleration phase) and a stop (deceleration, acceleration). According to this principle, we have set up a data analysis algorithm which looks into the data history and detects these phases. For each of them then, the algorithm identifies the areas of acceleration (cleaned of the posture angle) and finally provides (at discrete output times) the difference in position of the user.
The algorithm has been implemented as a complex state machine using proper software. The machine is able to work in an interactive manner between the different steps of motion (stop, walking forward, walking backward) and to identify the distance among points, by area analysis. Such an algorithm has shown to be more stable, accurate and consistent of the previous one, but conversely it produces its output with a noticeable delay with respect to the real-time integrator.
The final solution has implemented both algorithms in one scheme, a frequency mixer provides the best combination of the two subsystem outputs by compensating the readiness of the first solution with the accuracy given by the second.

5 Test and Results

The system has been integrated within a high-end 8bit microcontroller chosen to have enough computing and space capabilities to implement the above mentioned data acquisition, preprocessing and analysis algorithms. A summary schematics of the microcontroller circuitry is given in the figure below:

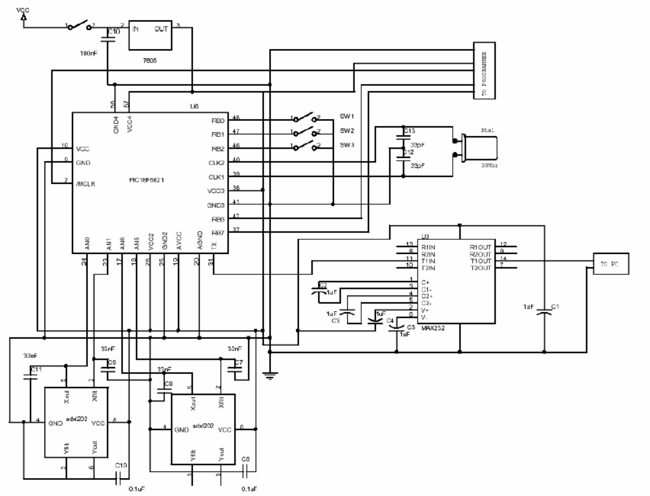

Figure 8: Diagram of the acquisition and control unit

System tests have been related both to the planar 2D integration, as well as with the interaction in the VE. The following test have been performed:

1) planar motion in 2D ;
2) spatial motion in VE,

In the first case we measured the accuracy of the planar integration algorithm in the latter we investigated the level of comfort that the sensor can provide to user during motion in VE. The bi-dimensional analysis was investigated with geometrically closed path (the starting point coincides with the endpoint). Test trajectories were examined both in the case of axis aligned motion (to simultaneously verify the noise rejection properties along the unused axis), as well as on mixed axes motion. In the two figures below some experimental data were reported:
In the first case, one square (twelve centimetre edge) has been used as reference path to move the sensor. In the figure, the red line shows the ideal trajectory while the blue lines the integrated one. Error has been measured as relative (percentage) spatial integration over absolute path length. A typical error of about 4% (0.04 m/m) was found.

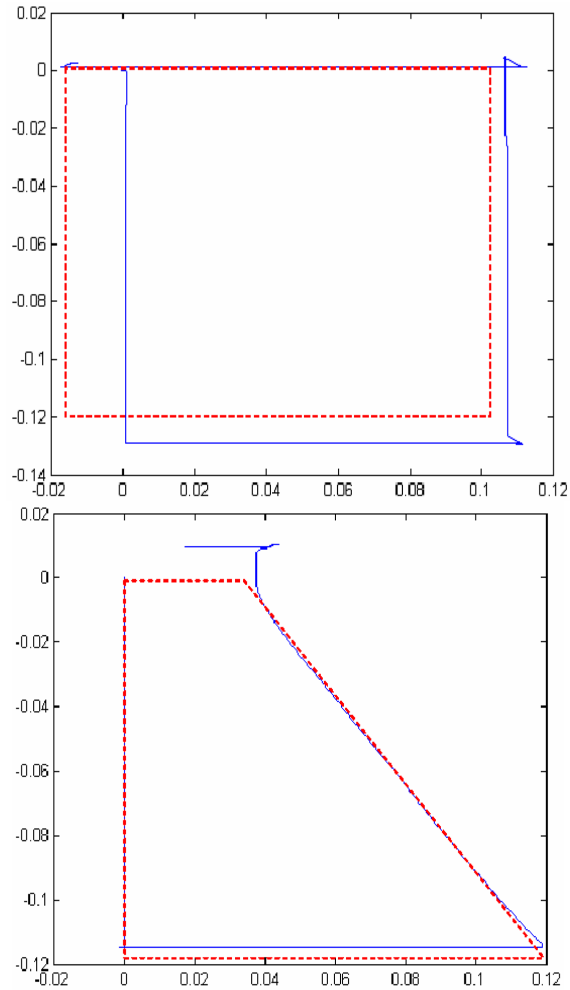

Figure 9: closed loop motion

These tests were executed in open loop (i.e. without any visual feedback presented to the user) and only measure the absolute accuracy error achieved during the integration. This condition (as in figure 9) will result in an un-accurate tracking of the reference borders (dashed/red line). In this case a 6mm error was produced in the first edge (upper horizontal), 0.07 mm in the second (vertical) and so on. Obviously in the absence of feedback these motion errors can cumulate to wider final motion errors, but, as proven in the second test, the case of fully immersion in VE compensate for them.

In the second set of experiments the user was completely immersed within a virtual environment. Being the coordinates in this space "unrelated" to physical distances, there was no possibility to retrieve an exact measurement for the integration error. The chosen experiments were therefore arranged as follows: an ideal trajectory was shown to the user (see last figure), and he was requested to follow it. The closed loop provided by the user feedback always allowed to cancel the steady state error, while during motion some compensation were required.

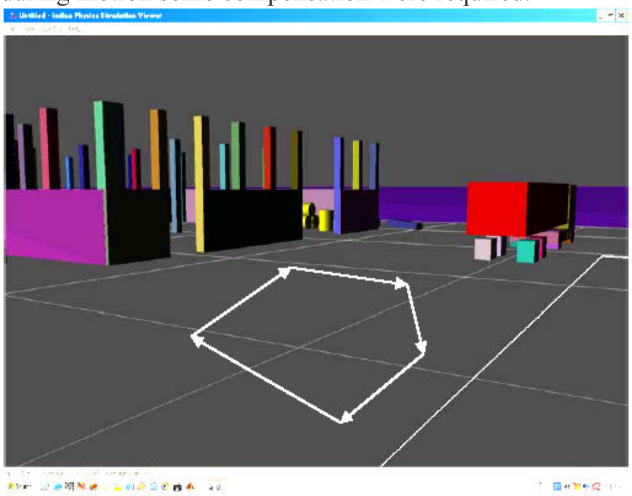

Figure 10: Test in VE

6 Conclusion

A novel type of device has been assembled for the interaction with virtual environments, the physical device is composed of 6 linear accelerometers arranged on a common couple of glasses. An embedded computer system allows signal acquisition, preprocessing and analysis in order to provide a remote computer with a six DOF motion subsystem.

The device was arranged as a means of interaction in immersive Virtual Environment, but according to its features it can be user as input device for several applications, such as: medical analysis, remote device control (tele-guidance), simulators,…

The preliminary experiments don in the laboratory have shown that the overall error in the planar case was within 4%, while closed loop experiments have shown a good degree of interaction between user and system.

Notwithstanding the system development is still at early stages, confortable results have already been achieved and they suggest working to improve data analysis and system integration. Future developments will also consider the possibility of integration with novel 3axial acceleration sensor as well as MEMS gyroscopes, in order to improve the accuracy of the asset measurement.

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