

Inertial proprioceptive devices: Self-motion-sensing toys and tools

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One of the current goals of technology is to redirect computation and communication capabilities from within the traditional computer and into everyday objects and devices—to make smart devices. One important function of smart devices is motion sensing. A proprioceptive device has a sense of its own motion and position. This ability can allow pens to remember what they have written, cameras to record their positions along with images, and baseball bats to communicate to batters information about their swing. In this paper, inertial sensing is introduced as the logical choice for unobtrusive, fully general motion sensing. Example proprioceptive device applications are presented along with their sensing ranges and sensitivities. Finally, the technologies used in implementing inertial sensors are described, and a survey of commercially available accelerometers and gyroscopes is presented.

As technology redirects *intelligence* away from the desktop and into everyday objects, common devices such as appliances, clothing, and toys are given computational sensing and communication abilities. This technological movement is exemplified in such research initiatives as the MIT Media Laboratory's *Things That Think* projects and Xerox PARC's concept of *Ubiquitous Computing*. While much of the associated work centers around devices that sense and respond to the motion, presence, or state of people and objects in their surroundings (examples include three-dimensional mice, smart tables, and smart coffee cups), this paper focuses on devices that have a sense of *themselves*, particularly a sense of their own motions. Embedded with inertial sensors, these devices are capable of autonomously sensing their own motions and orientations and reacting accord-

ingly. As a result, they are called *inertial proprioceptive devices*.

Devices with this self-motion-sensing ability can monitor their motions and respond to them. Consider a hand-held personal digital assistant (PDA) containing inertial sensors. Such a device could allow its user to move through complex information spaces by physically moving or tilting the PDA in the corresponding direction. To go a step further, an inertial-sensing user-controlled device with a sense of its own functionality could assess its state and give its user appropriate feedback. For example, a baseball bat could give batting tips, or juggling balls could teach a novice to juggle.

Motion sensing is not a new idea. For years, security systems, weapon systems, and medical and entertainment systems have employed various forms of “externally referenced” motion-sensing technologies such as infrared, radar, and video. Internally referenced, autonomous motion sensing has also existed for quite some time. Robots, aircraft, automobiles, and other vehicles have sensed and measured their motions for decades, using varying electromechanical sensors as well as inertial sensors.

Most of the motion-sensing technologies referred to above are restricted in terms of where and how they

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Table 1 Cost, size, and performance of selected inertial sensors from the 1970s to 1990s

Sensor Type	Date	Bias Stability (deg/hr)	Size (in ³)	Price (\$U.S./axis)
Electrostatic Gyro (ESG), Rockwell†	1970s	0.02 (1 naut.m/hr)	50–100	17000
Expected near-term†† navigation and military gyros	1990s	0.02 (1 naut.m/hr)	10–20	5000–10000
Expected near-term†† general consumer gyros	1990s	10	0.01–1.0	1–10

† = ESG references include 1 and 2 in the cited references
†† = With reference to Kumar et al.³

are useful. Infrared, radar, and video motion-sensing technologies are all “externally referenced,” physically removed from the moving object of interest. As a result these sensing modes are subject to occlusions and numerous interferences and noise sources. Although cars and aircraft measure their own motions, their motion sensors are both dimensionally and directionally limited. The motion sensor of a car wheel requires the friction of a road and only senses in one dimension; a pitot tube only works for an aircraft traveling forward in familiar atmospheric conditions.

A more tractable and generally effective type of motion sensor is the inertial sensor. Used in spacecraft, aircraft, and submarines for years, this type of sensor attaches directly to the moving body of interest and gives an output signal proportional to its own motion with respect to an inertial frame of reference. Two types of sensors comprise inertial sensing: accelerometers and gyroscopes. Accelerometers sense and respond to translational accelerations; gyroscopes sense and respond to rotational rates. Inertial sensors are desirable for general motion sensing because they operate regardless of external references, friction, winds, directions, and dimensions. However, inertial systems are not well-suited for absolute position tracking. In such systems, positions are found by integrating, over time, the signals of the sensors as well as any signal errors. As a result, position errors accumulate. Inertial systems are most effective in sensing applications involving relative motion.

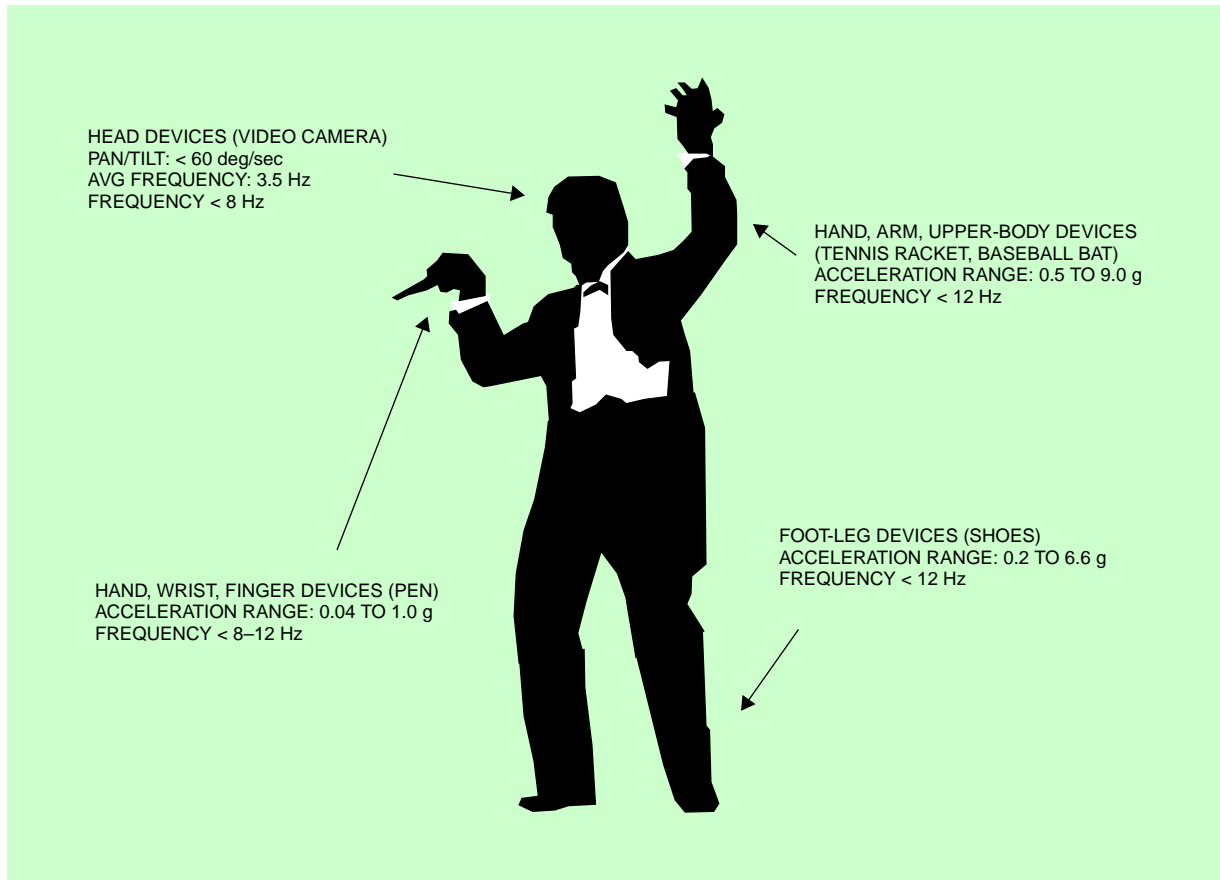
Until recent years, inertial sensors have only found use in the few fields mentioned above, since their cost and size have traditionally been quite prohibitive (see Table 1). Since their inception, these sensors have largely been complex and expensive electromechanical devices. Accelerometers have been made of relatively large mechanical proof masses, hinges, and servos; gyroscopes have been built with multiple mechanical gimbals, pick-offs, torques, and bearings. Recent advances in microelectromechanical system (MEMS) technologies have enabled inertial sensors to become available on the small size and price scales associated with such commonplace devices as consumer appliances. These advances are largely a result of batch processing techniques developed by the time-keeping and microelectronics industries.³

In this paper, several types of new motion-sensing applications are described along with corresponding sensing ranges and sensitivities. Then a brief introduction to general inertial measurement systems is given. Finally, the technologies used to implement accelerometers and gyroscopes are described, and representative commercial inertial sensors are surveyed.

Example proprioceptive applications

Motion sensing of common objects such as shoes and pens has long existed in one form or another. Treadmills have measured people’s walking speeds and distances. PDAs sense the path of a pen tip as a user

Figure 1 Characteristic motions of common human-controlled devices



writes on them. And computer programs analyze the optical flow of digitized video to infer camera motion. Each of these forms of motion detection requires an externally displaced device to actually sense motion.

Inertial sensors do not require external references, and since they are becoming inexpensive and smaller in size, they offer a new means of autonomous motion detection for devices that have long been dependent on external references (i.e., shoes and treadmills). Both the automobile and computer industries have quickly found uses for inertial sensing. In the automotive market, car navigation and air-bag control are the main inertial applications; the consumer computer market is seeing new input devices that can be used in three-dimensional space such as inertial mice and head trackers for virtual reality. The inertial market for these two industries is estimated to be in the range

of four billion dollars a year over the next several years.¹

Current work at the MIT Media Lab is focused on giving ordinary devices autonomous motion-sensing capabilities, via inertial sensing, so that as pens write, shoes walk, and cameras move, these objects sense their own motions without need for external references. The following subsections describe several example applications of human-controlled motion-sensing devices and the characteristics of their related motions. Figure 1 summarizes the characteristic input motion levels for general user-controlled devices. For each application, estimated motion data ranges are given along with experimentally recorded ranges. The experimental motion data were gathered both from video analysis and from a three-axis accelerometer-based inertial measurement unit (IMU) with a range of

± 10 gs, where g is the acceleration constant due to gravity. This IMU used Analog Devices' accelerometer model ADXL05, a type of capacitive pendulous accelerometer to be described later.

Pen. Personal digital assistants and signature verification devices both employ forms of handwriting recognition—each analyzes the path of a pen tip on a writing surface. If a pen is given inertial sensors and on-board computation and memory resources, it can sense its motions while it writes and use those motion data to estimate its time-varying position. By employing a pattern recognition method such as a neural network or hidden Markov model⁴ on its time-varying pen tip position, the pen can *know* and remember what it has written. Such a “smart” pen could not only save notes and letters but also send electronic mail (e-mail), solve mathematical problems, check for spelling errors, and carry out other standard computer operations.

An estimated range for pen tip accelerations was found by videotaping the pens and papers of several people as they signed their names. Pen tip velocities and radii of curvature of a number of characters were used to calculate the corresponding centripetal accelerations, which ranged from 0.1 g to 1.0 g.

Pen tip accelerations in the two-dimensional writing plane were also recorded using the aforementioned IMU attached to a pen tip. Recorded handwriting accelerations ranged, with uniform distribution, from 0.04 to 0.66 g.

The frequency of motion for handwriting will be estimated as the approximate natural frequency of the wrist and hand, 8 to 12 hertz (Hz), and should not exceed 20 Hz.⁵ When the relative size and motion scales are considered, the handwriting characteristic frequency described here will act as the frequency limit for other applications such as foot-, leg-, and arm-controlled devices.

Camera. Many current video analysis schemes attempt to extract camera motion from optical flow.⁶ Optical flow is the apparent motion of image intensity on the image plane of the camera over time. A number of models exist that relate this two-dimensional optical flow motion with its corresponding three-dimensional camera motion. Such optically based motion estimation schemes are best suited for static scenes, where the only motion on the image plane is that caused by camera motion. In most cases, however,

video cameras are not used to record static scenes. If a video camera can sense its own motions inertially and record its motion data along with the video, subsequent camera motion analysis can be performed solely by using the inertial data, or a joint inertial-optical motion estimator⁷ can be implemented with a state-estimation scheme such as an extended Kalman filter.

The required sensing capabilities for a motion-sensing camera can be estimated by looking at the rates of movement of typical camera maneuvers. Camera movement rates were experimentally found by monitoring the pan and tilt motions of a hand-held video recorder throughout a series of shooting sequences. An average rotational rate of about 36 degrees per second (deg/sec) was observed. Pan rates varied from near zero deg/sec up to about 60 deg/sec. These rotational rates determine the input range for gyroscopes used in a motion-sensing camera.

Characteristic camera motion frequency can be estimated as that of human head motion. Head motion frequency averages about 3.5 Hz and rolls off around 8 Hz.⁸ Inertial sensors used for tracking a video camera should thus have optimal frequency response in the 3 to 8 Hz range.

Shoes. Just as most types of vehicles have speedometers and odometers, shoes should also be able to sense and track their motions. The medical and athletic fields have relied on various forms of externally referenced walking rate and distance sensors for some time. Shoes embedded with an inertial-sensing system would allow walking-sensing to be carried out unobtrusively and in any setting. An inertial shoe pedometer system would work much like the pen and camera described above; inertial sensors would record shoe motion components, and an on-board computer would estimate speed and distance traveled. Given sufficient computational, memory, and sensing resources, a proprioceptive shoe system could not only tell its wearer how far and fast he or she is walking, but could also diagnose gait abnormalities or alert the wearer that it is time to replace the shoe soles.

For a benchmark estimate of the shoe accelerations associated with walking, consider an average person's walking speed of 3.5 miles per hour (mph) (5.13 feet per second, or fps) or 2 steps per second.⁹ The centripetal acceleration of a shoe traveling 5.13 fps about an average adult's knee of radius 2.17 ft¹⁰ is 12.1 ft/sec² (about 0.4 g).

Experimental values of walking foot accelerations were obtained with the previously mentioned IMU fastened to a shoe near the ball of a foot while walking. Recorded accelerations ranged from 0.19 to 6.57 g, with nearly all the acceleration activity located near the mean of 1.59 g.

Given the estimated walking accelerations, inertial sensors used for shoe motion tracking should have an input range of about ± 10 gs.

Bats, rackets, and batons. The final example application area includes toys and tools that are swung or waved expressively by their users. A baseball bat or tennis racket that senses its motions can tell a player how fast he or she is swinging, and if used with other sensors and a microprocessor, could give feedback information about a player's performance.

An application with similar motion-sensing requirements is the "Digital Baton,"¹¹ which was developed at the MIT Media Lab. This device, using an orthogonal accelerometer triad for motion sensing and several pressure sensors for analog finger inputs, allows its user to "conduct" and control computer music orchestrations simply by being moved and gripped in different ways.

Using the test IMU, hand accelerations were recorded during athletic arm- or hand-swinging motions. An acceleration range of 0.49 to 9.02 g was found. Most of the acceleration activity was concentrated near the mean value of 2.2 g.

Baseball bat accelerations for the typical swing of a youth (bat speed of 40 mph, 58.7 fps)¹² are estimated as the centripetal acceleration. These accelerations will serve as an upper limit. If a swinging arm length of 2 feet and a distance of about 10 inches from the hands' position to the center of mass of the bat is assumed, the bat will experience a maximum acceleration of $(58.7 \text{ fps})^2/2.8 \text{ ft} = 1230 \text{ ft/sec}^2 = 38 \text{ gs}$! At the same time, the handle of the bat will undergo an acceleration of about $(29.3 \text{ fps})^2/2 \text{ ft} = 429 \text{ ft/sec}^2 = 13 \text{ gs}$.

Given the motion range estimates for these athletic and expressive hand and arm applications, any inertial sensors measuring the motion of a user's hand or arm needs to have an upper input limit of near 10 to 15 gs. If the motion of an object extending from the user's body (like a baseball bat) is to be sensed, a greater input range (about 50 g) is necessary.

General inertial measurement systems

Motor-cognizant devices like those mentioned in the preceding sections can independently track their motions using inertial sensors. As mentioned earlier, inertial sensing is accomplished with two types of sensors: accelerometers and gyroscopes. Typically, both of these sensors are sensitive to only one axis of motion. Inertial navigation systems (INSs) used in aircraft, spacecraft, and other vehicles are ordinarily based on an inertial measurement unit that consists of a set of three orthogonal accelerometers and three mutually orthogonal gyroscopes. Such a device is sensitive to the full six degrees of freedom of motion (three translational and three rotational). It should also be noted that rotation can be measured inertially without gyroscopes, using the differential linear accelerations measured by two (or more) accelerometers undergoing the same rotational motion but located at different distances from the center of rotation.

INSs determine position and orientation from the basic kinematic equations for translational and rotational motion. The orientation of an object, given a sensed rotational rate, ω , during each time step, t , is given by

$$\theta = \theta_0 + \omega t \quad (1)$$

where θ equals the orientation angle, and t equals the time step. The output of a gyroscope is the rotational rate ω . Similarly, position is found with the translational kinematic equation

$$x = x_0 + v_0 t + \frac{1}{2} a t^2 \quad (2)$$

where x equals position, v equals velocity, and a equals acceleration, the output of an accelerometer.

A schematized inertial measurement system for a general proprioceptive device is shown in Figure 2. This system consists of a set of sensors whose signals go through an analog-to-digital converter to a microcontroller. The sensors include accelerometers and gyroscopes as well as a temperature sensor (because the signals of most inertial sensors are temperature-dependent) and any other sensors called for by a given application. The microcontroller either stores the sensor data for later use, or it performs some type of real-time analysis and invokes the appropriate output.

Several types of computation and analysis may be performed with the data of the inertial sensors by the microcontroller of the system. The most basic micro-

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