Integrated Systems and their Impact on the Future of Positioning, Navigation, and Mapping Applications

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Key words: GPS, Inertial Systems, Navigational Aid, Vision-Based Systems

ABSTRACT

The Global Positioning System (GPS) is a constellation of satellites that broadcast signals that can be used to derive precise timing, location, and velocity information. The derived information (time, position, and velocity) may be combined with other systems such as communications devices, computers, and software to perform a variety of tasks. The Global Positioning System (GPS) is capable of providing all range positioning accuracy in all situations where uninterrupted signal reception is possible and the general satellite geometry is within acceptable limits. It is also evident that other navigation technologies, such as Inertial Navigation Systems (INS), are currently not capable of providing similar accuracies at a comparable price, i.e. there is no real competition to GPS in a scenario of uninterrupted signal reception. This leaves two scenarios to be considered. The first one is that of intermittent signal reception, as for instance in heavily forested areas or in urban centres. The other one is that of no signal reception at all, as for instance in buildings, underground or underwater. In the first case, GPS has to be integrated with other sensors to bridge periods of no signal reception. In the second case, GPS has to be replaced by another system that can provide continuous navigation in those environments where GPS does not work. Both cases will be treated in this paper where the integration of systems and navigational aids (navaids), will be investigated as an alternative for times of no GPS signal reception. In terms of systems, both INS and vision-based systems will be considered. In terms of navaids, odometers, gyros and digital maps will be considered for land vehicle navigation, and pedometers, magnetic compasses, digital maps, and cellular phones for backpack systems.

Integrated systems will, therefore, provide a system that has superior performance in comparison with either a GPS, an INS, or vision-based stand-alone system. For instance, GPS derived positions have approximately white noise characteristics over the whole frequency range. The GPS-derived positions and velocities are therefore excellent external measurements for updating the INS and providing the imaging sensors with position parameters, thus improving its long-term accuracy. Similarly, the INS can provide precise position and velocity data for GPS signal acquisition and reacquisition after outages and the orientation parameters for the vision-based system. The vision-based system can be used as a backup navigation system and to update the INS data if the GPS signal is blocked for long periods. In general, the fact that redundant measurements are available for the determination of the vehicle trajectory parameters greatly enhances the reliability of the system.

The paper will cover both, the concept of integration and implementation aspects of integrated systems. Examples on current and future systems for mapping, positioning, and navigation applications will be given.

1. INTRODUCTION: CURRENT INTEGRATED POSITIONING AND NAVIGATION MARKET

The current market of integrated positioning and navigation systems is clearly dominated by those systems that have GPS as one of their components. Besides being globally available, GPS provides the whole range of navigation accuracies at very low cost. It is also highly portable, has low power consumption, and is well suited for integration with other sensors, communication links, and databases. At this point in the development of navigation technology, the need for alternative positioning systems only arises because GPS does not work in all environments.

Figure (1) shows the projected development of GPS module cost. For the accuracy range considered here, it has reached the unit price of about $100 and predictions are that it will drop to about $50 by 2005 when, most likely, it will level off. Module cost are not equivalent to system cost, but the recent development of navigation receivers at a price of a few hundred dollars shows clearly that module cost are an important factor. Even more important is the fact that with unit cost that low, GPS is becoming a commodity, comparable to a Sony Walkman, pocket calculators, or a digital wristwatch. Thus, personal GPS devices will soon start to drive the module market and provide navigation receivers of high versatility at even lower cost.

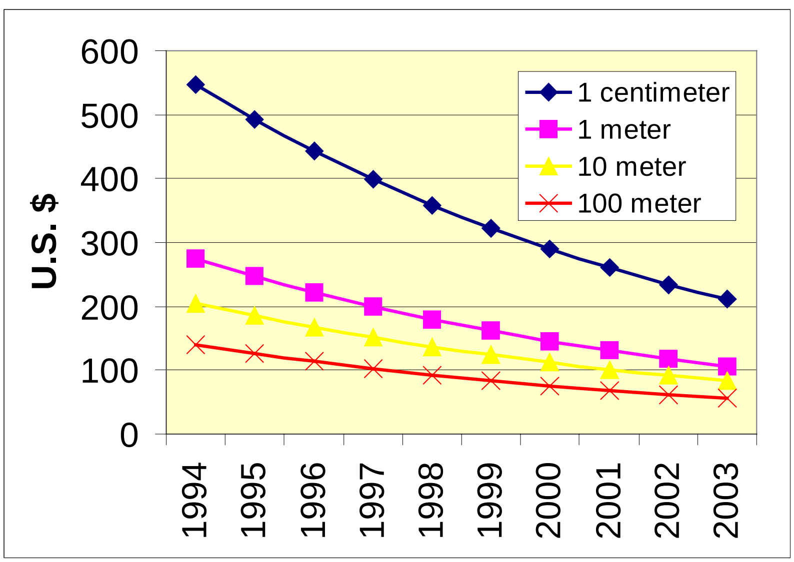

Figure 1: Price Development of GPS Module Cost by Accuracy
(After NAPA/NRC, 1995)

Considering these market projections shown in Figure (1), it is very difficult for any other positioning and navigation technology that to compete with GPS (Schwarz and El-Sheimy, 1999). Therefore, other navigation technologies would typically be developed for 'non-GPS' environments, i.e. for environments where GPS does not function at all (underground, underwater, in buildings) or where it performs poorly (forested areas, urban environments). Although there is still a substantial navigation market for 'non-GPS' environments, it is much smaller than the one predicted for GPS. In the portion of the market where GPS is only available for part of the time, the question will be 'how much is the user willing to pay for a continuous navigation solution'? This obviously will depend on the specific application and it might be possible that niche markets will develop around such applications. Integrated solutions will be of high interest in such applications, and may involve sensor integration as well as data base integration for applications such as map matching. In those applications where GPS does not work at all, the search for cost-effective alternatives will continue.

One promising development is the emergence of Micro-Electro-Mechanical Systems (MEMS) technology. MEMS is an enabling technology with a massive global market, predicted to be at 140 billion US $ in 2002. This means that it will have about 7 times the market size of GPS at that time. A small portion of this market, about 2%, will support inertial sensor technology. Since INS technology is capable of working in all environments where GPS has difficulties, MEMS inertial technology is seen as both a possible complement of GPS technology and a potential alternative to GPS if market volumes develop in the way anticipated, for more details see DARPA (1998), and U.S. D.o.D. (1995).

Besides the MEMS technology development, there is also an increasing trend towards integrated systems. The integration of GPS with low-cost IMUs has already reached the product stage. Such systems can either be used as a highly reliable navigation systems, giving position, velocity, and attitude with high accuracy, or as a georeferencing systems for various imaging sensors (optical or digital cameras, laser scanners, multispectral scanners). Integration of low-cost sensors, specifically for backpack systems has also made considerable advances. The use of vision-based systems in conjunction with low-cost position and attitude sensors may become a viable alternative in cities if current advances in enabling technologies continue. Specifically the development of digital cameras on a C-MOS chip, the availability of inexpensive storage devices of Gigabyte capacity, and the increase in computer speed to 1000 MHz. Will contribute to the emergence of low-cost vision-based systems (Schwarz and El-Sheimy, 1999).

2. STATUS OF CURRENT INTEGRATED SYSTEMS

The GPS is capable of providing positioning and navigation paramters in all situations where uninterrupted signal reception is possible and the general satellite geometry is within acceptable limits. It is also evident that other navigation technologies are currently not capable of providing similar accuracies at a comparable price, i.e. there is not real competition to GPS in a scenario of uninterrupted signal reception. This leaves two scenarios to be considered. The first one is that of intermittent signal reception, as for instance in heavily forested areas or in urban centres. The other one is that of no signal reception at all, as for instance in buildings, underground or underwater. In the first case, GPS has to be integrated with other navaid sensors to bridge periods of no signal reception. In the second case, GPS has to be replaced by another system that can provide continuous navigation in those environments where GPS does not work. In terms of systems, both INS and vision-based systems (mainly for robotics applications) are the most commonly used systems. In terms of navaids, odometers, gyros and digital maps will be considered for land vehicle navigation, and pedometers, magnetic compasses, digital maps, and cellular phones for backpack systems.

The integration of the navigation technologies (GPS, INS, and vision-based technologies) with navaids provides a system that has superior performance in comparison with either a GPS, an INS, or vision-based stand-alone system. For instance, GPS derived positions have approximately white noise characteristics over the whole frequency range. The GPS-derived positions and velocities are therefore excellent external measurements for updating the INS and providing the imaging sensors with position parameters, thus improving its long-term accuracy. Similarly, the INS can provide precise position and velocity data for GPS signal acquisition and reacquisition after outages and the orientation parameters for the vision-based system. The vision-based system can be used as a backup navigation system and to update the INS data if the GPS signal is blocked for long periods. In general, the fact that redundant measurements are available for the determination of the vehicle trajectory parameters greatly enhances the reliability of the system.

The navigation states vector (position, velocity, and attitude) can be determined by judicially combining elements of: navigation technologies (e.g. GPS, Inertial, and vision-based) and navigation aids (e.g. distance, velocity, and attitude sensors). This is shown in Figure (2) where the navigation technologies and navaids are listed in two blocks. Table (1) lists current and possible integrated systems scenarios. Table (2) lists which sub-vectors of the Navigation State that can be obtained with these systems scenarios and which characteristics and the resulting integrated system will have. Possible applications are then given in the last column.

The Tables indicate that a wide variety of integration strategies can be implemented. Each has its own characteristics and the choice of a specific system will be based on system requirements and applications. Although it is possible to integrate any set of technologies, the integration of GPS and INS represents the core of for any integrated systems where reliability and versatility are the major issues. The low cost of GPS receivers, the coverage and reliability of GPS, and the expected decrease in cost of MEMS-based inertial sensors make GPS and INS the logical technologies for realizing the benefits offered by integrated positioning systems. Many companies are currently working on the integration of MEMS based IMU with GPS, with projections of size, weight and power at 2 x 2 x 0.5 cm, 5 g, and less than 1 W for implementation at the ASIC level. Figure 3, shows typical performances for some of the scenarios listed in Table 1.

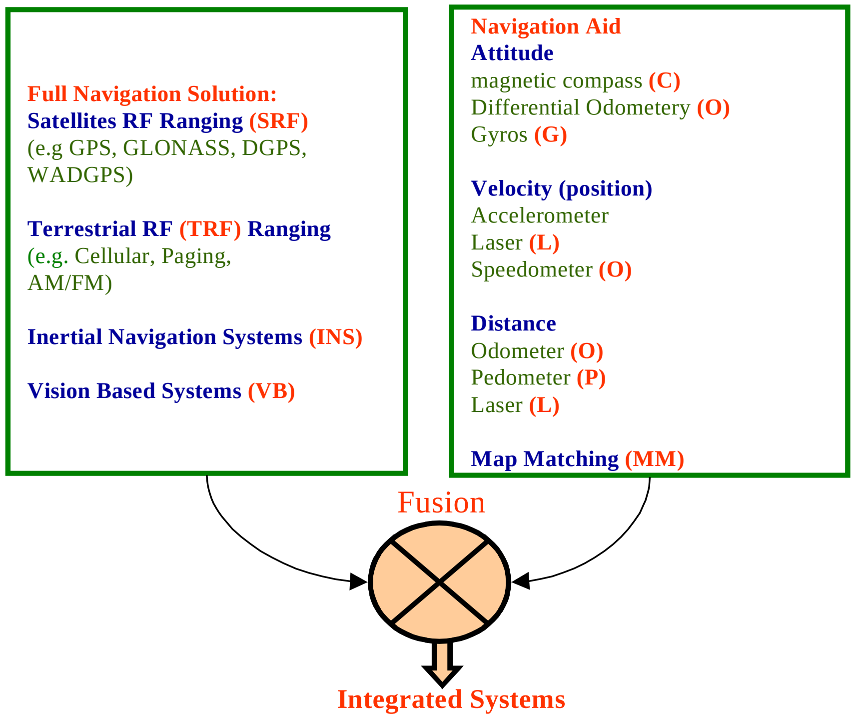

Figure 2: Concept of Integrating Navigation Systems and Navaids.

Table 1: Integrated Systems Scenarios

Scenario		Navigation Systems				Navigation Aids (navaids)							Application	
		SRF	TRF	VB	INS	MM	L	O	P	C	G	A	Vehicle	Backpack
Current Systems	**1**	√	√										√	√
	2	√			√								√	√
	3	√		√	√								√	
	4	√				√							√	
	5	√						√			√		√	
	6	√							√	√		√		√
	7	√					√				√		√	√
Possible Systems	***8***	√		√							√			√
	9	√		√			√				√			√
	10*	√						√					√	
	11	√					√			√				√
	12		√			√							√	
	13		√					√			√		√	
	14		√						√	√		√		√

Table 2: Characterstics, Lmitations, and Applications of Systems Scenarios

Scenario	Navigation State			Characteristics/Current Limitations	Applications	
	r(t)	v(t)	R(t)		Vehicle	Backpack
1	√	√		• Low cost/lightweight system • Signal blockage in urban centers	Car navigation Fleet Management	Hikers Rescue operations
2	√	√	√	• Works in all environments • High Cost/Weight	Military Navigation Mapping	Seismic Applications
3	√	√	√	• Works in all environments • High Cost/Weight	Highway inventory systems	
4	√	√		• Low cost/lightweight system • Signal blockage in urban centers	Car navigation	
5	√	√	√*	• Low cost/lightweight system • Provides heading only • Signal blockage in urban centers	Car navigation	
6	√	√		• Low cost/lightweight system • Signal blockage in urban centers		Navigation
7	√	√	√*	• Static mode of operation for backpack • Provides heading only	Mapping applications	Mapping applications
8	√	√	√*	• Static mode of operation • Provides heading only		Mapping applications Target tracking
9	√	√	√*	• Static mode of operation • Heading only		
10	√	√		• Low cost/lightweight system • Signal blockage in urban centers	Car navigation	
11	√	√	√*	• Provides heading only • Signal blockage in urban centers		Targeting tracking
12	√			• Low cost/lightweight system • Local coverage • Provides heading only	Car navigation	
13	√		√*	• Low cost/lightweight system • Local coverage • Provides heading only	Car navigation	
14	√	√	√*	• Low cost/lightweight system • Local coverage • Provides heading only		Navigation

- Provides heading only

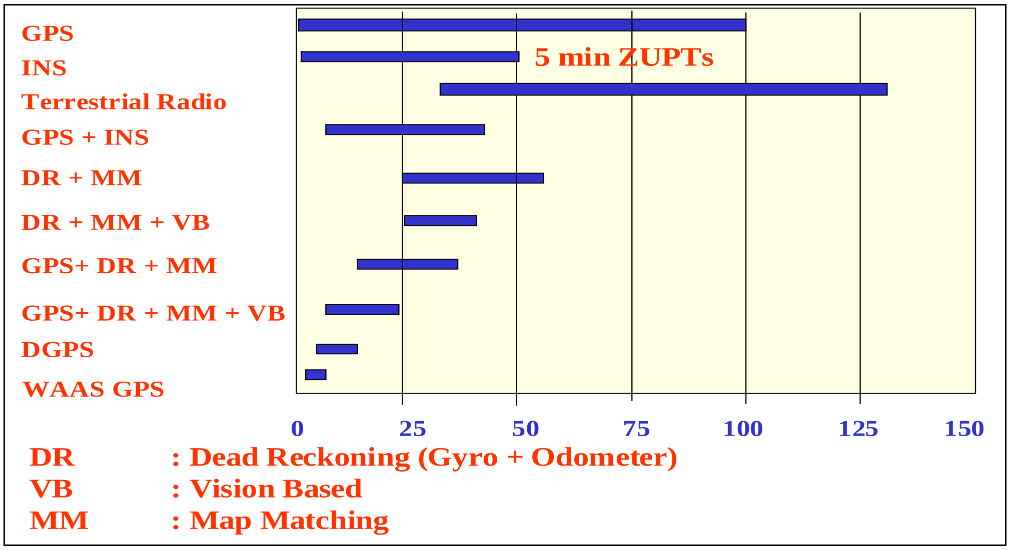

Figure 3: Performance Comparisons of Various Integrated Systems

3. FUTURE TRENDS

The trend towards integrated systems in positioning and navigation is fuelled by the demand for high accuracy, lightweight, low cost, and by technological developments which satisfy this demand. Three developments are especially important in this context: the progress in MEMS based INS systems, future enhancement to GPS, and future trends of vision-based systems and map matching. There is no question that that GPS will be part of any future integrated system, if GPS signals can be received for at least part of the time

The Progress in MEMS Technology: The Progress in MEMS Technology will enable in the near future complete inertial navigation units on a chip, composed of multiple integrated MEMS accelerometers and gyroscopes. In addition to single-chip inertial navigation units, there are many opportunities for MEMS insertion into low-power, high-resolution, small-area displays and mass data storage devices for storage densities of terabytes per square centimeter. These opportunities are essential if vision based systems are to be fully integrated into a backpack integrated navigation system.

Figure (4) relates the predicted development of MEMS-based inertial sensors to three major performance parameters - bias, scale factor and noise. These parameters are usually considered when judging system accuracy. They show that, for the medium term, two conclusions are possible at this time. First, MEMS-based inertial sensors will in general reach higher performance levels than the MEMS-based IMU-on-a-chip. This simply indicates that performance is dependent on the physical dimensions of the sensor or system. Second, it appears possible that MEMS-based tactical IMUs will become a reality within a ten year time frame, but that navigation-grade systems are rather unlikely during that period. For more details see Schwarz and El-Sheimy (1999), Barbour (1996), and Allen et. al. (1998).

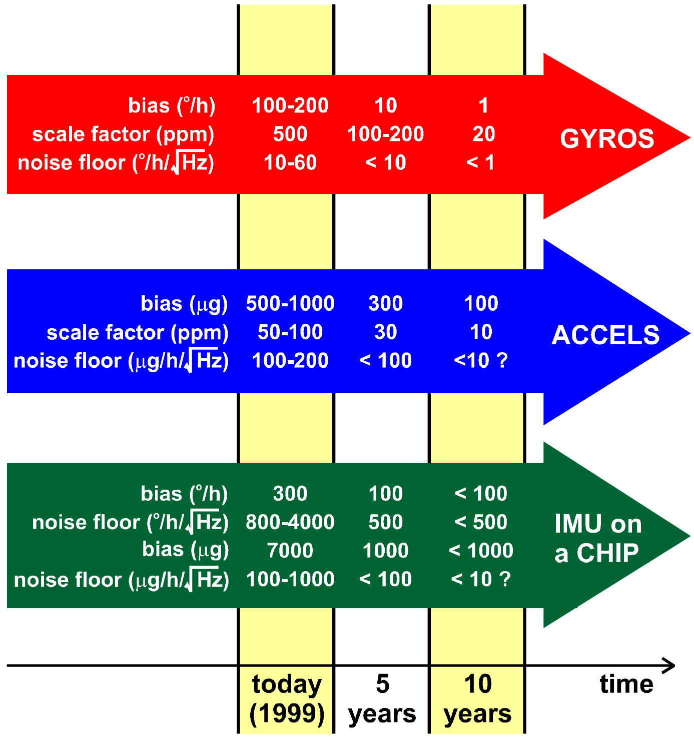

Figure 4: Predicted Development of MEMS-Based Inertial Sensors

The Future Enhancement of GPS: The proposed enhancements to GPS have the common goal of increasing both the capability and robustness of the system. The possible major modifications to the system include the removal of the intentional degradation of the signals (SA), the introduction of new signals, improvements in the control segment functions and increases in the size of the GPS constellation. The potential effects of these have been lumped together and are shown in Figure (4). It is estimated that they will improve the 2DRMS to about 9.5m. These are long term goals and no firm commitments have yet been made.

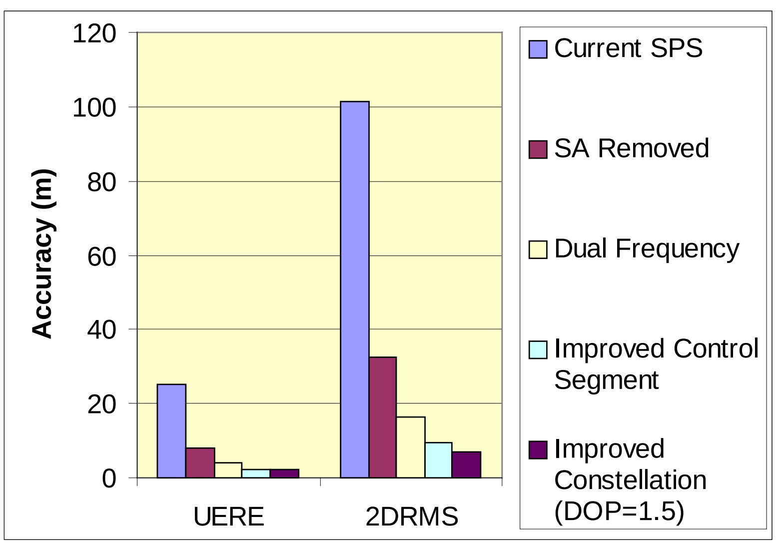

Figure 5: Improvements in GPS Single Point Accuracy Due to Potential Improvements (Average DOP = 2.0 Unless Otherwise Marked).

Figure (5) shows the following (for more details see Schwarz and El-Sheimy, 1999 and NAPA/NRC, 1995 report):

- Removal of SA: the removal of SA will improve the 2DRMS accuracy from 101.4 to 32.5m.
- New signals: under conditions of no SA, dual frequency corrections improve the 2DRMS from 32.5m to 16.6m.
- Increasing the Size of the GPS Constellation: this would result in an improvement of the 2DRMS from 9.5m to 7.1m, assuming that all of the other potential improvements named above have been implemented.
- Increasing the Size of the GPS Constellation: this would result in an improvement of the 2DRMS from 9.5m to 7.1m, assuming that all of the other potential improvements named above have been implemented.

Future Trends of Vision-Based Systems and Map Matching Techniques: Conceptually, the vision-based concept is very attractive. Current experimental systems are limited in range and are oriented towards robotics applications. Figure (6) shows the future trend in digital cameras prices, resolution, and weight. The price and weight are going down while the resolution is going up. VBS hardware (digital cameras, storage devices, portable computers) could currently support the development of an autonomous VBS at the level of 10K US$ and a weight less than 2 kg. This indicates that low-cost and lightweight systems based on digital cameras are feasible. The major challenges are algorithms and software that make their use in unstructured environments possible. Smart image matching and 3D modeling of the VBS environment are not at a stage to support such a development. What complicates the problem is that the currently market demand for a stand-alone VBS is limited.

Because of these problems, its not expected VBS will be implemented as stand-lone navigation system in the next 5 years that but rather as a component of an integrated system. Possible scenarios include GPS and INS. The integration of GPS/INS with vision systems has been used in a number of post-mission mapping applications (El-Sheimy, 1996, and Schwarz, 1998). The current limitation for their implementation as autonomous navigation systems for land and backpack systems is mainly due the size, weight, and cost of GPS and INS. The integration of VBS with MEMS-based tactical-grade IMU and a GPS chip can be seen as one solution to this problem. The exterior orientation parameters can in this case be determined by a combination of GPS and INS. The result is a series of georeferenced images, i.e. of images with their six parameters of exterior orientation 'stamped' on them. Once, this stamp has been put on the image, the time dependence has been eliminated, i.e. each image has a unique position and orientation in space. Therefore, the major part of image matching and modeling the 3D environments around the system is rather simple. Whether a prototype system can be built in the next 5 years will mainly depend on the cost of the MEMS-based tactical grade IMU. In a 10-year period such scenario will be more feasible as the cost of MEMS-based tactical-grade IMU will be at the level of \$500-\$1000. The second scenario is a navaid-based backpack system, which if foreseen to happen within the next 5 years. It will ingrate a VBS with navaid such as pedometers and compass (Judd, 1997). Current backpack systems that integrate GPS, pedometer, altimeter, and compass already exist. Their cost is about \$2000 and their weight less than 3 oz.

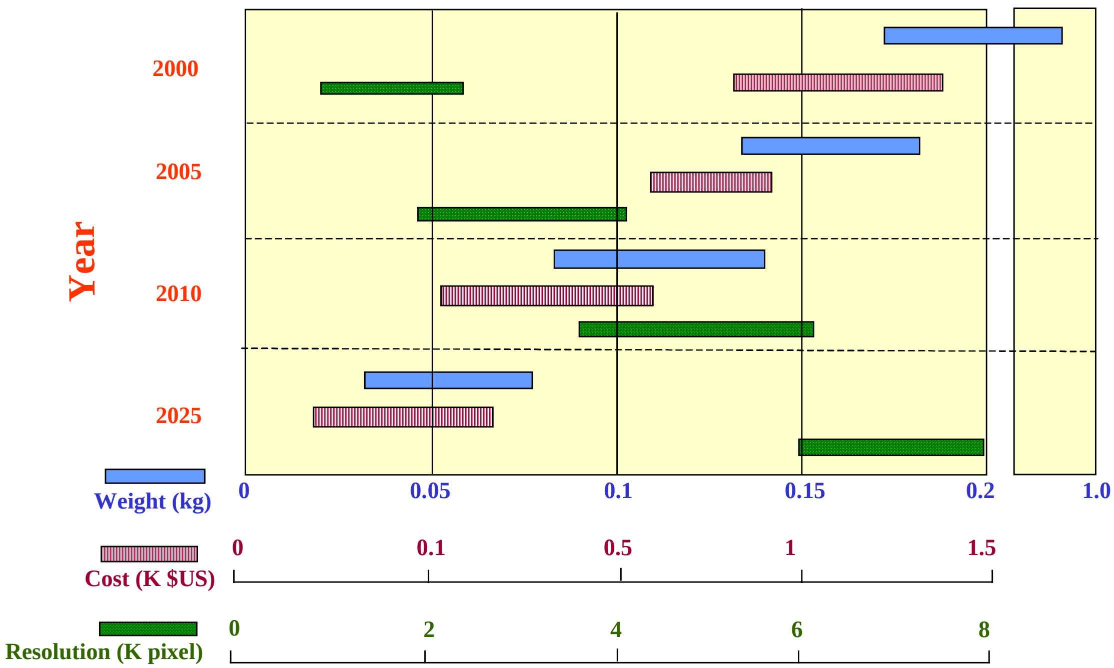

Figure 6: The Trend in Digital Cameras Prices, Resolution, and Weight

Although there are some problems with map matching, it has a number of advantages and is used in 25% of systems surveyed by Krakiwsky (1996). The map matching system is relatively inexpensive as it only requires cheap sensors, such as the odometer and/or the ABS (Anti-lock Braking System) pulses. There is no external infrastructure required and the accuracy of the system is fundamentally limited by the accuracy of the digital maps and the matching algorithm. Successful map matching is reliant upon maps that are complete and accurate to better than 30m absolute. This is becoming less of a problem as companies such as Navtech/EGT and Etak in the USA, Teleatlas in Europe, the Japan Digital Road Map Association, and Geographic Technologies (Telstra) in Australia have accurately mapped or plan to map the major cities, urban areas, and major highways in their region of interest. Finally, the development of portable navigation systems that are map-based should increase with the availability of less expensive, more intelligent digital road maps. A map-based personal navigation assistant (PNA) that supports path finding and route guidance for backpack applications is another development that may not be too far away.

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BIOGRAPHICAL NOTE

Dr. Naser El-Sheimy – is an Assistant Professor at the Department of Geomatics Engineering of the University of Calgary. He holds a B.Sc. and M.Sc. from Egypt, two post-graduate Diplomas in Photogrammetry and Remote Sensing from ITC, the Netherlands, and a Ph.D. from the University of Calgary. His area of expertise is the integration of GPS/INS/imaging sensors for mapping and GIS applications with special emphasis on the use of multi-sensor in Mobile Mapping Systems. He is now the chairman of the special study group for Mobile Multi-Sensor Systems of the International Association of Geodesy and the chairman of The International Federation of Surveyors (FIG) working group C5.3 on "kinematic and Integrated Positioning Systems”

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