CHALLENGING OLYMPIC MEDALS – AN INNOVATIVE GNSS-BASED MULTI-SENSOR SYSTEM FOR ATHLETE TRAINING AND COACHING

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ABSTRACT:

In preparing for Olympic competition, every detail is important. Athletes and coaches are not only interested in the physiological information, but also interested in the positional information. Physiological information can be relatively easy to obtain using relevant detectors. However, real-time high precision determination of the athletes' movement and the status of motion has been a challenging task. This contribution introduces the development of a smart real-time athlete monitoring and coaching system, which integrates a low-cost GPS, Micro-Electro-Mechanical System (MEMS) inertial measurement units (IMUs), magnetometers, wireless communication and other physiological sensors. Surveying, Positioning And Navigation (SPAN) group at RMIT University in collaboration with the Australian Institute of Sport and Catapult Innovations Pty Ltd. has embarked this innovative development of the patented system since early 2003. The system was initially designed for elite Australian rowers in both Athens Olympics and the Lucerne International Rowing Regatta and now it has been tested and used across a large number of sport activities, including rowing, canoeing, skiing, running, sailing, footballing etc. The current developments of the system, system architecture, field validation and potential applications are presented and further developments (e.g. the interpretation of data and customisation for individual players) and its commercial aspect of the project are also outlined. We hope that the 2008 Beijing Olympic Games will witness the significant roles of geospatial science has played in sport competition and quality improvement of recreational activities.

1. INTRODUCTION

In many sports, the margin between victory and defeat may be a matter of a few hundredths of a second. Certainly that is true of sport competition where the demands on equipment and the performance pressure on athletes are tremendous - and not just on elite athletes, but increasingly on participants at every skill level. Athletes and coaches are not only interested in the physiological information, e.g., blood oxygen, respiration and heart rates; but also interested in the position and movement information, e.g. position, velocity, acceleration and changes in direction. Physiological information can be relatively easy to obtain using relevant detectors, e.g., heart rate monitor, ergometer (O'Sullivan et al., 2003). However, real-time high precision determination of the athlete location and movement has been a challenge (Fyfe et al., 2001; Hutchings et al., 2000; Larsson, 2003; Wu et al., 2007).

In-depth understanding of sensor-based human performance measurement, such as the determination of a characteristic signature of the "perfect" movement, is required to analyse the performance of the athlete (Seiler, 2003). The position, movement (velocity and heading) and acceleration (i.e. force) information plays an important role in an effective analysis of the athlete performance. Athletes and coaches are not only interested in the trajectories of the movement, but also in the motion analysis of segments of the human or the orientation of equipment (e.g. lift-over of a motor cycle, torsion of skis). Therefore, the ability to measure and record positional information together with athlete physiological information in real-time is critical to the process of athlete training and coaching (Wu et al., 2007).

Traditionally, development and testing of materials or equipment for sport has been based on repeated measurements with resources including timing cells or wind tunnels. Similarly, the analysis of athletes' performance has relied on techniques such as measuring race segments (chronometry) and video recordings (Wägli and Skaloud, 2007). That is to say, positional information can only be measured in either well-controlled situation in dedicated sport laboratories or using simulation device (Zhang et al., 2004). These methods, however, appear vulnerable to changing meteorological conditions and the difficulty of replicating the posture and movement of test subjects from one trial to the next due to such facts as improved performance stemming from cumulative experience in the trials or decreased performance due to fatigue (Wägli and Skaloud, 2007). Furthermore, much of the equipment is either too heavy, expensive or obtrusive and multiple factors which are difficult to control have limited the use of sport-specific field testing (Zhang et al., 2003). Therefore, new methods that offer precise measurements during trials and subsequent evaluation of positions, velocities, acceleration and changes in direction would be a big leap forward (Wu et al., 2007).

Satellite-based positioning has already proven its effectiveness in many sports, including car racing and rowing (Edgecomb and Norton, 2006; Wägli and Skaloud, 2007; Zhang et al., 2003; Zhang et al., 2004). In an open space, Global Positioning System (GPS) supports continuous position, velocity, and acceleration analysis of athlete's trajectories. The environmental reality, however, is often far from such an ideal case. An athlete's environment quickly alternates between open spaces and areas that block or attenuate satellite signals (e.g. sudden satellite masking), which makes GPS signal reception difficult or even impossible. To overcome the lack of continuity of the GPS signals and in order to observe accelerations (and hence forces) directly, low-cost MEMS-IMUs are integrated with GPS. Such a combination is suitable for sport's application because of their small size and limited cost. Also, the GPS/MEMS-IMU integration enables accurate determination of the position, velocity and acceleration (Grewal et al., 2007; Titterton and Weston, 2004).

Surveying, Positioning And Navigation (SPAN) group at RMIT University in collaboration with the Australian Institute of Sport and Catapult Innovation Pty Ltd. has embarked an innovative development of a smart real-time athlete monitoring and coaching system since early 2003. This paper presents recent developments of the integrated sensors system. Performance of the low-cost code-only and carrier phase GPS modules is evaluated using high-end GPS systems. Two prototype systems are then introduced. Finally, a typical sport application is illustrated.

2. DEVELOPMENT OF PROTOTYPE SYSTEM

This research commenced in 2001 from the Australian Cooperative Research Centre (CRC) for Micro Technology, under Project 2.5 "Interface Technologies for athlete Monitoring". Established in July 1999 with a seven year grant, the CRC for Micro Technology has four major research areas: fabrication technology; microdevice packages; safety and health; and micro-fluidic devices (CRC microTechnology, 2003). The aim of the Project 2.5 is to develop unique monitoring equipment that is essentially unobtrusive, so that the athlete is virtually unaware of its presence in training and competition. The Project 2.5 initially investigates the feasibility using GPS to aid inertial devices for position, velocity and acceleration (PVA) determination in real-time. The positional information is then combined with other athlete physiological information and integrated into a dedicated electronic device for package and analysis, and relayed to the coach. The continuous monitoring of three-dimensional PVA of the athlete with a very high update rate and accuracy is achieved through an integration of GPS, an IMU/INS for athlete physiological information, a data communication mechanism, and interactive visual control using a Geographical Information System (GIS) (Wu et al., 2007).

Table 1 outlines the major phases of the system development (Wu et al., 2007). The Stages I, II, III and IV have been completed and stages V is under intensive development. In stages I, II and III, the performance of low-cost GPS has been evaluated using high-end GPS receivers. In stage IV, a prototype system has been developed and used in rowing training and coaching. In stage V, an upgraded system is developed. The GPS chip, MEMS IMU and wireless communication device have been integrated in the final (compact) system. Online calculation and GIS services will be also integrated in the future development to make the system user friendly.

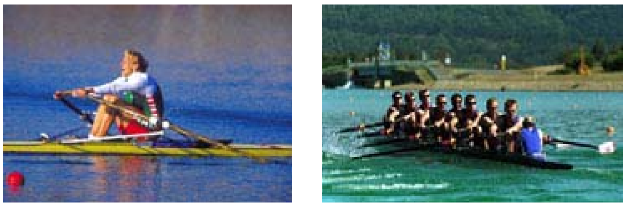
2.1 The Sport of Rowing

Rowing is a highly developed and becomes an increasingly popular international sport. It combines a wonderful spectacle with a heated competition. Rowing races usually cover a distance of 2,000 m in river, canal or lake-type competition environment in six lanes. To win the competition, athletes have to qualify through four pre-determined rounds: the preliminary round (heats), the repeat round (repechages), the semi-finals and the finals. The "A" final determines the first six places and the runners-up "B" final determines the next six places (i.e. 7th to 12th positions). The number of rounds per event depends on the number of crews taking part.

Stage	Hardware	Software	PVAT
I	iPAQ+PC, Genius 1, support circuit, active/patch antenna	WCE and Win2000/ XP based software	Post-processing, low update rate
II	iPAQ, Genius 1, support circuit, active/patch antenna	WCE based software	Real-time, low update rate
III	MCU, SuperStarII, MCU built-in support circuit, patch antenna	MCU based firmware	Real-time, high update rate
IV	ROVER-2004: Chip-level, Fastrax GPS chips, built-in circuit, active/patch antenna, wireless communication	MCU based firmware	Real-time, high update rate
V	minimaxX: Chip-level, GPS, IMU and magnetometer chips, built-in circuit, active/patch antenna, wireless communication	Win XP based software / MCU based firmware	Real-time, high update rate

Table 1. Major development milestones of the smart integrated tracking system (PVAT – Position, velocity, acceleration and time)

The races are judged under the supervision of umpires, who are members of the Jury for the event. The jury members are placed at various locations on and off the competition course, such as the starting line, where the races begin under the supervision of the aligner and the starter; along the course of the race in the competition lanes under the supervision of umpires; the finishing line with the finish-line umpire; the identity verification stage of the crews before their embarkation onto the boats; the weighing-in of the athletes; the weighing-in of boats; and, in general, in all areas directly related to the competition, the athletes and their equipment (Athens Olympics, 2004).



(a) Sculling events (b) Sweep-oared events

Figure 1. Sculling (two oars used, one in each hand) and sweep-oared (one oar with both hands) scenarios in Olympic competition

There are 14 different boat classes raced in Olympic rowing. These include eight sculling events in which two oars are used (see Figure 1a), one in each hand and six sweep-oared events in which the rowers use one oar with both hands (see Figure 1b).

The sculling boat classes are the single, the double and the quadruple sculls with crews of one, two or four athletes respectively, as well as the lightweight double. The sweep row categories include the pair, the four, the lightweight four (for men only) and the eight with coxswain.

2.2 Rowing Phases and Monitoring

A rowing stroke is a precise movement with rowers using their legs, back and arms to generate power. A stroke begins with the placing of the blade in the water and ends with the re-emerging of the blade from the water and positioning for another cycle. The rowing stroke can be divided into four main phases: catch, drive, finish and recovery (Isaacs and Mulligan, 1999; Rower's World, 2003) (see Figure 2). These sequential phases must flow from and into each other to produce a continuous and fluid movement.

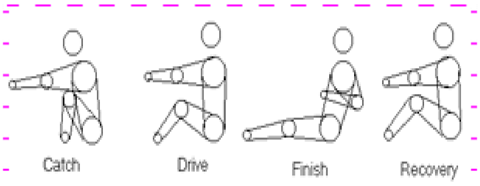


Figure 2. Schematic diagrams showing the four main sequential phases (i.e. catch, drive, finish and recovery) in a rowing stroke and the position of head, arm and legs of the rower).

At the catch, the blade is placed into the water quickly with minimal disturbance to the boat. The rower's arms are extended outward, torso is tilted forward, and legs are compressed. A good catch produces a minimal amount of back and front splash and causes no check. The catches of all crews of a boat must be identical. Out of step catches (unsynchronisation) causes balance problems and reduce a boat's speed. The blade must be fully squared to the water at the catch (*ibid*).

The boat gains its speed on the drive. In this part of the stroke, the oarsman applies power to the oar with forces from arms, back and legs, and swings his torso away from the stern of the boat. The handle of the oar is pulled in a clean, powerful and levelled motion towards the bow of the boat with a constant force.

At the finish, the oarsman finishes applying power to the oar handle, removes the blade from the water sharply, and feathers the oar (rotate it by 90º) so that the blade becomes parallel to the surface of the water.

At the recovery, rowers are given a brief rest to prepare for the next stroke. The oarsman must slide towards the stern of the boat and prepare the blade for the next catch. Crews exhibit an approximate 2:1 ratio between the times spent on the recovery and the times spent on the drive. At the end of the recovery, the oar is gradually squared and prepared for the catch (Mickelson, 1979).

Understanding which movements should occur in each phase of the stroke allows coaches to design effective conditioning programs and evaluate rowing performance effectively (Seiler, 2003). Success in competitive rowing is achieved by taking the shortest time to complete a course (usually 2000 m) which directly links to the average velocity of the boat. Acceleration is proportional to force since the boat is accelerated as it reacts with the sweeping arc of the oar. Three factors affecting boat velocity, power, length and rate, are important determinants of rowing performance. The power provides how fast the boat travels in a stroke, the length is associated with how far the boat travels in each stroke and the rate striking provides how many strokes are rowed per minute (Xiao et al., 2003). Therefore the rower must achieve an optimal combination of high stroke power, long stroke length and high stroke rate.

Figure 3 presents the stroke signals captured using geodetic-type GPS receivers. It is demonstrated that the signals captured provide a clear picture of the rowing stroke phases as described above. In this particular stroke, the graph indicates that the rower has harmonised well in his stroke cycle by using appropriate time (1:2) in the catch and the drive.

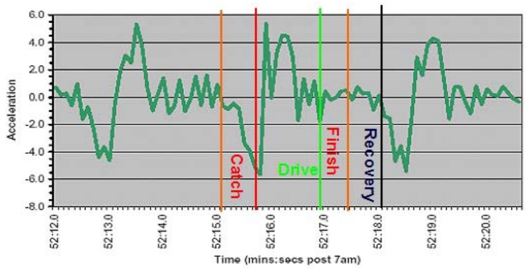


Figure 3. Schematic rowing stroke signature captured from high precision GPS measurements

2.3 Evaluation of Low-cost, Low Update Rate Code GPS

A number of critical factors contribute to the applicability of the GPS system to sport applications. This includes the precision, cost, volume and weight of the system, and its integration with other sensors including accelerometers, communication mechanism, and a personal digital assistant (PDA). Because of the challenges of diverse applications and a broadening market, the low-cost GPS has evolved significantly during the past decade. Increasingly miniaturised device has been developed into even wearable and embedded into other devices. For financial consideration the tracking of a large number of athletes requires the use of low-cost, single-frequency GPS receivers. The current pricing of dual-frequency GPS receivers means that their use will be restricted to a few athletes and applications with high position-accuracy requirements (Wägli and Skaloud, 2007). Thus, the research presented here integrates low-cost single frequency GPS with other sensors that take into consideration the high dynamics of the athletes and their particular environment.

An important component of the research is to evulate the performance of a low-code GPS receiver before it is integrated into a sport application system. A rowboat test has been conducted to compare the low-cost, code-only GPS receiver with high-end dual-frequency receiver, Trimble 5700. The low-cost, code-only GPS receiver used is a Genius 1 manufactured by Rojone (2003), and based on SiRF GPS chipset. These two types of GPS receiver are mounted on a rowboat and tested in a rowing race course in Canberra, Australia.

Figure 4 shows the differences in velocity determined simultaneously from the low-cost code-only GPS and the high-end dual-frequency GPS. Assuming the carrier velocity from

Post-Processing Kinematic (PPK) derived velocity has an average accuracy in the order of ~0.03 m/s. The results confirm that the accuracy specification of 0.1 m/s from the manufacturer is correct for more than 95% of observations. It is demonstrated that low-cost code-only GPS receivers can provide accuracy position, velocity and acceleration information.

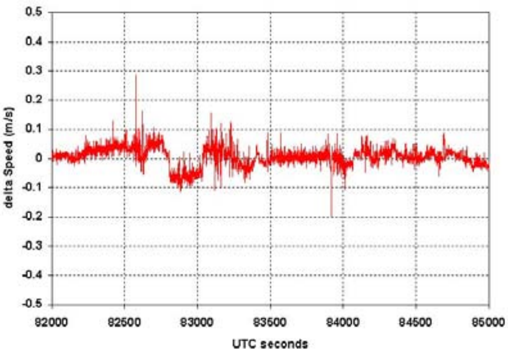


Figure 4. GPS velocity differences between code and RTK solution

2.4 Evaluation of Low-cost, High Update Rate Carrier Phase GPS

An athlete monitoring and coaching system with the functionality to output PVA information at a high update rate has been found necessary and essential in many sport applications. The GPS velocity and acceleration can be derived either in the position domain or the range domain using a differentiator. As the GPS position is usually derived from the pseudorange measurements, the position error is of the order of several to tens of metres. The derived velocity and acceleration are therefore very noisy and inaccurate. The position solution derived from carrier phase measurements is much more accurate and less noisy. But such a solution needs multiple dual-frequency receivers, i.e. through forming double-differenced carrier phase measurements to derive the baseline solution. Such an implementation is too expensive and awkward for a MEMS-based sensor system. The implementation in the range domain is relatively sophisticated. The velocity and acceleration can be derived from the Doppler measurements or from the carrier phase measurements (Li et al., 2006). Another benefit of the low-cost GPS receiver with carrier phase measurement is that the accuracy of position can be improved using the carrier smoothing technique. Carrier phase smoothing is a process that combines the absolute but noisy pseudorange measurements with the accurate but ambiguous carrier phase measurements to obtain a good solution without the noise inherent in pseudorange tracking through a weighted averaging process (Misra and Enge, 2006).

To evaluate the performance of the low-cost, high update rate carrier phase GPS, a mini-bus experiment is conducted in Yarra Bend Park, Melbourne in 2003. A RTK GPS system (Trimble 5700 receivers) is again used for a "ground-truth" reference. Obviously, the RTK solution is precise enough for this purpose when evaluating the 10 Hz update rate GPS solution. A low-cost, high update rate, carrier phase GPS is used in this system to obtain the range velocity and acceleration. A Canadian Marconi Company's (CMC) SuperStar II GPS OEM board (Novatel Inc., 2007) is used to form the hardware basis of the system. The SuperStar II can provide PVA solution at a rate up to 5 Hz as well as raw measurements (i.e. code, carrier phase and signal-to-noise ratio) at a maximum rate of 10 Hz.

Figure 5 represents the position discrepancies (latitude and longitude) between solutions derived from code-only and carrier-smoothed measurements respectively (compared with RTK solution again). The carrier-smoothed solution has smoothing lines and the code-only solution is noisy. Figure 6 depicts the difference of two velocity solutions derived from the 10 Hz GPS receiver and RTK GPS solution respecively. The result shows that the average and stand deviation of the difference are 0.005 m/s and 0.088 m/s respectively. Because the obstruction of buildings and trees in the urban environment, the discontinuity of GPS solutions is evident.

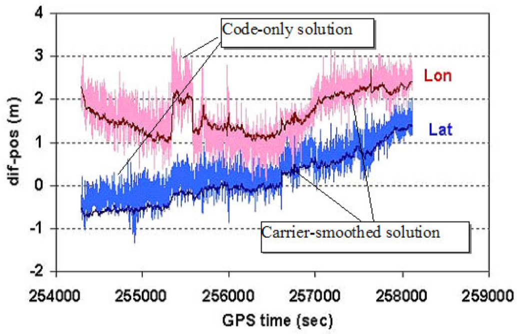


Figure 5. Position differences between 10 Hz low-cost GPS (code-only and carrier-smoothed solutions) and RTK GPS solutions

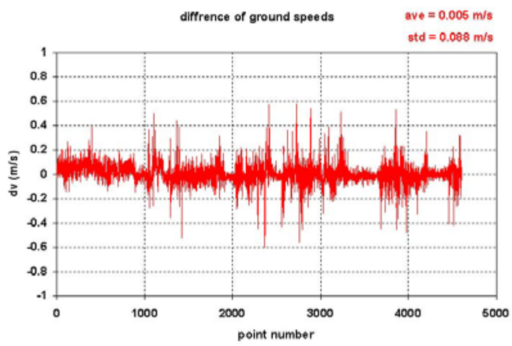


Figure 6. Velocity differences between 10 Hz low-cost GPS and RTK GPS solutions

It has clearly demonstrated that carrier-smoothed solution can reduce the level of noise of code-only solution efficiently. However, slow-variation errors such as SVs' ephemeris and atmosphere errors are still present in the carrier-smoothed solution.

2.5 Prototype Athlete Monitoring and Coaching Systems – ROVER-2004 and minimaxX

In 2004, a prototype athlete monitoring and coaching system, namely ROVER-2004, was developed initially for rowing training and coaching (Zhang et al., 2004). Figure 7 shows the prototype system, ROVER-2004, which integrates a low-cost GPS and wireless communication. The GPS receiver used is a *Fastrax iTrax03* chip which is a low-cost single frequency receiver with carrier phase measurements.

Robust algorithms and associated software/firmware have been developed using a number of special treatments to suit for rowing-specific applications. These algorithms are evaluated through a number of static and kinematical trials using high precision RTK-GPS (Wu et al., 2007).

Figure 7. A compact prototype rower monitoring and coaching system (ROVER-2004) with 10 Hz carrier GPS capability and wireless communication.

As aforementioned, an athlete's environment can change dramatically between open spaces and areas where GPS signal reception is difficult or even impossible due to obstruction. To overcome the problem of GPS signal continuity and observe accelerations directly, low-cost MEMS IMUs are integrated with GPS chips. A new version of athlete monitoring and coaching system, namely minimaxX, has been developed (Wu et al., 2007).

Figure 8. A compact prototype athlete monitoring and coaching system (minimaxX) with high update rate carrier phase GPS capability and wireless communication

The minimaxX is designed as a low-cost, wearable and integrated positioning device including a low-cost GPS, MEMS IMUs, and three magnetometers aligned with three orthogonal axes. The dimension of the minimaxX is approximately 8×5×4 cm (see Figure 8). The GPS receiver is a Fastrax iTrax03 chip (Fastrax, 2007).

3. SPORT APPLICATIONS

The ROVER-2004/minimaxX systems were initially designed for elite Australian athletes in both Athens Olympics and the Lucerne International Rowing Regatta and now it has been used across a large number of sport activities, including rowing, canoeing, skiing, running, sailing, cycling and footballing etc. (see Figure 9) (Wu et al., 2007; Zhang et al., 2004). The latest, but typical Australian Football League application of the minimaxX was launched in May 2007 (Wu et al., 2007). A stream of new AFL specific functionalities has been developed. For example, the minimaxX system has been coupled with a powerful on board computer and long range wireless communication for up to 100 units simultaneously, and it can broadcast performance summaries for coaches or the media to use in real time. Specific functionality has been developed for real-time monitoring and post-training analyses of footballers. The following discussion is concentrated on rowing application in Olympics.

Figure 9. Some typical examples of ROVER-2004/minimaxX systems' sport applications (e.g. sailing, canoeing, footballing, half pipe, rowing, mogul skiing, cycling and skiing)

Figure 10. James Tomkins and Drew Ginn who won men's pair gold medal in Athens Olympics

The Athens 2004 Olympic Games Rowing events were held at the Schinias Olympic Rowing and Canoeing Centre over a period of nine competition days, from 14 to 22 August 2004. A total of 550 athletes (358 men and 192 women) from all over the world took part in 14 rowing events. 45 (28 men and 17 women) Australian rowers took part in 11 rowing events (Athens Olympics, 2004). The ROVER-2004 was used by Australian rowers prior to and during the Athens Olympic Games. Three Olympic rowing medals were won by Australian athletes. Figure 10 shows James Tomkins and Drew Ginn who won men's pair gold medal in Athens Olympics. The Beijing 2008 Olympic Games Rowing events will be held at Shunyi Olympic Rowing-Canoeing Park on the side of Chaobai River in Shunyi District of Beijing from August 9-17, 2008. A total of

550 athletes (350 men and 194 women) from all over the world will take part in 14 rowing events (Beijing Olympics, 2008). We hope the 2008 Beijing Olympic Games will witness the significant roles of geospatial science has played in sport competition and improvement of our quality of recreational activities

4. CONCLUSION

This paper presents the latest developments of a smart real-time athlete monitoring and coaching system, which integrated a low-cost GPS, MEMS IMUs, magnetometers and wireless communication. The current developments of the system, system design, validation and applications have been outlined. The proof-of-concept trials are successful and the feasibility of GPS technology to assist in elite athlete training has been confirmed. Prototype systems have been developed and used at the elite level across a large number of sports activities.

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