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GNSS for sports – sailing and rowing perspectives

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Abstract. This paper introduces two sport-related projects conducted by the Satellite Positioning and Orientation Research Team (SPORT) at RMIT University – the speed sailing world record challenge and development of a smart GPS rower tracking system. In the first project, both traditional and contemporary surveying technologies are investigated to assist the Macquarie Speed Sailing Team to reliably record and subsequently claim a world speed sailing record. In the second project, an integrated rower tracking system has been developed in collaboration with other research partners and the system has been used prior to and during the Athens Olympic Games. Three Olympic rowing medals were won by Australia. The technology, research procedures and major developments are presented.

Key words: GNSS for sports, low-cost GPS, speed sailing, rowing

1 Introduction

The School of Mathematical and Geospatial Sciences RMIT University has been involved in a number of sports related research projects in the past few years. Two notable projects are: (1) the world sailing speed challenge and (2) Development of a miniaturised, high precision GPS rower monitoring and coaching system. The aim of first project was to identify the best technology to help the Macquarie Speed Sailing Team improve their sailing speed recording. The second project is funded by the Australian Cooperative Research Centre (CRC) for microTechnology, under Project 2.5 "Interface Technologies for Athlete Monitoring". An aim of Project 2.5 is to develop monitoring equipment that is essentially unobtrusive such that the athlete is virtually unaware of its presence in training and competition. This also includes investigation into the acquisition and interpretation of sport's data and its meaningful presentation to both coaches and athletes (CRC microTechnology, 2003).

1.1 World sailing speed record project

World Sailing Speed Records are awarded by the World Sailing Speed Record Council (WSSRC, 2002), an affiliated body of the International Sailing Federation (ISAF, 2002). Eligible records are average velocities over a 500-metre course by a yacht whose only method of propulsion is the natural action of the wind on the sail. A record will only be ratified if the attempt has been monitored by a commissioner appointed by the ISAF/WSSRC. The course may be defined by floats on the water or by transit posts on shore and a timed run is the difference between start and finish times recorded to the nearest one hundredth of a second. Speed, distance divided by time, is calculated to the nearest one hundredth of a knot with allowance made for the resolved component of any tidal stream and/or current flow on the course. A course is deemed unsuitable if the tidal flow and/or current exceed one knot.

This paper presents an analysis of both GPS and video methods of determining sailing velocity. Simulations of GPS position recording and video recording were made during a recent record attempt by mounting a GPS receiver and the video camera on the Macquarie team's support boat (a power boat) and making three runs along the marked course. Comparing the GPS-derived velocity with the video-derived velocity is a useful means of benchmarking GPS velocity against an approved ISAF/WSSRC technique. In addition, a Kalman filter is used to verify a simple method of determining approximations to instantaneous velocity from kinematic GPS.

1.2 CRC for micro technology rower tracking project

The five-year project, "Development of a miniaturised, high precision GPS rower monitoring and coaching system", initially investigated the feasibility of 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 to package, analyse and relay the information to the coach. The continuous monitoring of three-dimensional PVA of the rowing boat with a very high frequency and accuracy is achieved through an integration of GPS, an inertial navigation system with sensors for athlete physiological information, a data communication mechanism, and an interactive visualisation procedure.

The ability to measure and record athlete physiological information (eg. aerobic capacity, strength training and endurance performance) and positional information associated with athlete movement in real-time is critical in the process of athlete training and coaching. Blood oxygen (oxygen consumption), respiration, heart rates (myocardial and hemodynamic responses), velocity, acceleration/force, changes in direction and position, and many other factors are required in elite athlete training and coaching. The position, movement (i.e. velocity and direction) and force (i.e. acceleration) information plays an important role in effective analysis of the athlete performance, especially for rowers. For example, the stroke rate, force and synchronisation of athletes are critical for the performance of rowers in a competition.

Currently, the stroke information can only be measured in either well-controlled situations in dedicated sports laboratories or using simulation devices. 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. Reliable analysis of the stroke rate and stroke length in rowing has been a challenge for a long time due to the unavailability of the real scenario data, in particular high-precision PVA data (Larsson, 2003). Existing technologies used for this purpose include theoretical studies (eg. Zatsiorsky and Yakunin, 1991), video-footage procedure (Kleshnev, 2001), indoor tank procedure (Lin et al., 2003), computer modelling (Atkinson, 2003; Kirtley and Smith, 1996) and ergometer (Upson, 2003; Elliott et al., 2003). Therefore, smart real-time monitoring during training and competition to help elite athletes to improve their performance and avoid injuries is critical for both athletes and coaches.

This paper introduces an innovative "smart" GPS rover tracking system that is currently under development at SPORT, RMIT. This paper first outlines the main phases in a standard rowing stroke for a better understanding of the specific technique. The paper then briefly summarises the proposed research methodologies for the project and presents some selected results of recent tests. Promising results have been obtained using low-cost GPS. It has shown that low-cost, code-only GPS can provide great potential for rowing applications and the stroke signature captured from GPS is of great value for rowers and their coaches. A prototype system has been built and the system was extensively used by Australian rowers prior to and in the Lucerne Regatta and Athens Olympic Games where a number of gold medals were won.

2. World sailing speed records

World Sailing Speed Records (WSSRC, 2002) are established in sail area divisions:

- ✓ 10 Sq. m Class: up to and including 10 m^2;
- ✓ A Class: from 10 m^2 up to and including 150 square feet (13.94 m^2);
- ✓ B Class: from 150 square feet up to and including 235 square feet (21.83 m^2);
- ✓ C Class: from 235 square feet up to and including 300 square feet (27.87 m^2); and
- ✓ D Class: over 300 square feet.

The fastest of these class records also becomes the outright World Sailing Speed Record.

In 1993 at Shallow Inlet, Simon McKeon and Tim Daddo, sailing the triplanar wing sail yacht *Yellow Pages Endeavor*, captured the B, C and D Class WSSRs on the way to recording the highest speed ever attained by any craft under sail of 46.52 knots. They achieved these multiple records by adjusting the area of the wing sail between runs. *Yellow Pages Endeavour* was designed and constructed by Lindsay Cunningham and raced by a group of volunteers. In March 2002, the group, then known as the Macquarie World Speed Sailing Team attempted to raise their own record above 50 knots with a new yacht *Macquarie Innovation* (see Fig. 1). This yacht, an improvement on *Yellow Pages Endeavour*, is a solid wing sail attached by aerofoil sections to three small pontoons, one of which contains the skipper and crew. In the right wind and sea conditions, with the skipper steering and the crew trimming the wing sail, the crew capsule lifts clear of the water and the yacht rises slightly, planing on the pontoons. Small hydrofoils under the pontoons assist the hull planing and offer side force resistance as well as steering control from the front pontoon.

Both *Macquarie Innovation* and *Yellow Pages Endeavour* are developments of the speed potential exhibited by C Class catamarans, the yachts that contest the Little America's Cup – a challenge cup, like the America's Cup, where a sailing club challenges the cup holder (another sailing club) to a series of match races. McCrae Yacht Club on Port Phillip Bay, Victoria won the cup in 1985 with *Victoria-150* and defended it successfully until 1996. *Victoria-150*, designed and built by Lindsay Cunningham, was the first C Class to effectively use a multi-slotted aerofoil wing section as a sail (Landmark, 2002).

2.1 Time recording of the sailing record attempts

Timing of the record attempt by the Macquarie team employed a "clever, low-technology" solution developed by the team in previous attempts and now embodied in the ISAF rules. It uses a video camera mounted in the crew capsule and aimed to capture images of the transit posts onshore. The camera is capable of recording images at 25 frames per second. The transit posts, placed 8m apart in pairs, define start and finish lines of the 500m course (see Fig. 2). As the yacht passes the start line the video camera records an image of two starting posts in transit and some time later, crossing the finish line,

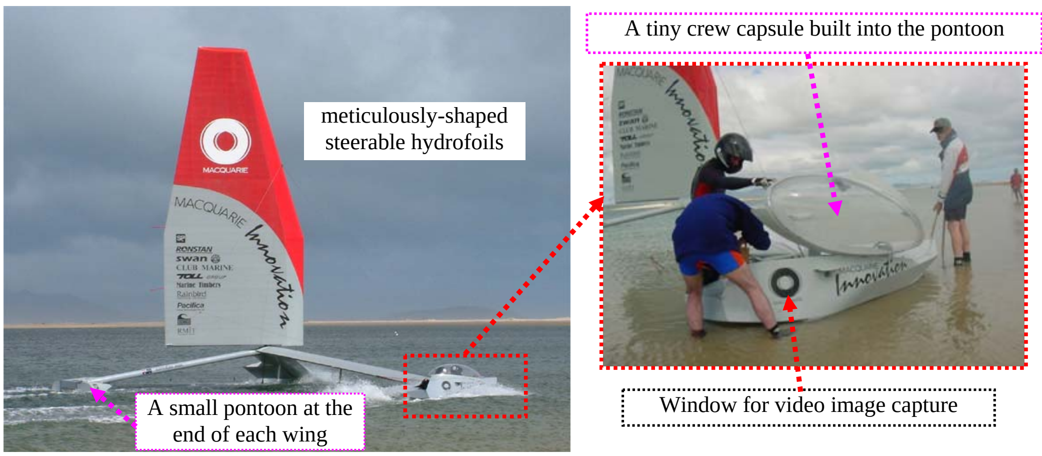

Fig. 1 Images of the Macquarie Innovation – a triplanar asymmetrical wing-sail yacht

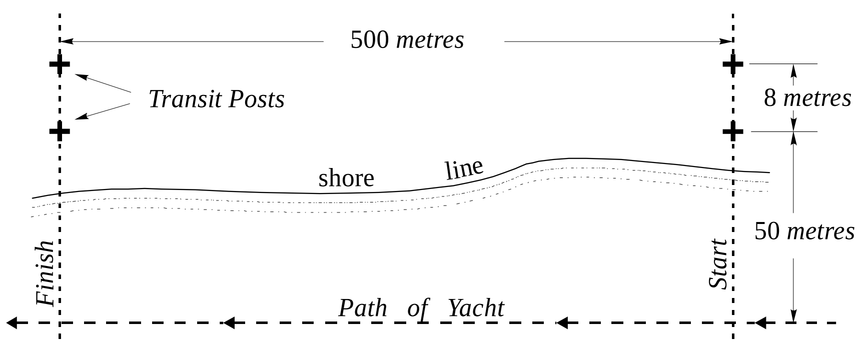

Fig. 2 Schematic plan of transit posts defining the course

(a) video image frame "*n*" just before crossing finish line

(b)transit post pair surveyed by both total station and GPS

(c) video image frame "*m*" just after crossing start line

Fig. 3 Diagrammatic view of the transit posts surveyed by both conventional and GPS methods (b) and video image frames "*m*" and "*n*" at the start (c) and finish (a) records another image of the finish posts in transit (see Fig. 3).

After a run on the course, the video is reviewed frame by frame, noting the frame numbers *m* and *n* showing the start and finish transits. Subtracting frame numbers and multiplying by the frame rate gives the elapsed time, which divided into the distance yields the average speed.

2.2 GPS and the transit post recording procedure

This timing technique, video camera and transit posts described above, presents some difficulties and restrictions for competing teams. These include:

- The positioning of the transit posts is critical; not only must they produce parallel transit lines but these lines must be at least 500m apart and approximately perpendicular to the path of the yacht. This requirement necessitates a survey to mark the positions of the posts and a plan endorsed by a surveyor to satisfy the ISAF/WSSRC commissioner.
- The yacht is restricted to sailing close to the shore (and transit posts) so that video images of transits are clear and distinct.
- Since the yacht must travel relatively close to the transit posts and at a great speed, there is some danger to the crew if the yacht becomes uncontrollable and collides with the transit posts.
- The direction of the shore (and hence the course) limits the allowable wind direction since a yacht's maximum potential speed is restricted to a narrow range of wind angles from the direction of travel.
- The video camera must be calibrated to ensure an accurate frame rate.
- Reviewing the video images is a time consuming process and is subject to human error (errors in visually interpreting the actual transit).

Recognising these restrictions, the Macquarie team approached the School of Mathematical and Geospatial Sciences, RMIT, with a proposal to investigate the use of on-board GPS as a more flexible means of determining sailing velocity and distance. GPS has the following attractions and possible advantages over the present method.

- GPS is a proven robust positioning technology, well documented in the surveying and geodetic literature. When used in *kinematic differential* mode, GPS is capable of determining positions at centimetre level precision at precise and regular time intervals as small as 0.1 sec.
- Kinematic Differential GPS positioning removes the restriction of marked courses. Positions can be determined at time intervals, say $\Delta t = 0.1\,\sec$, independent of the yacht's sailing direction. Differences in position divided by time differences, yield velocity. In addition, simple velocity plots can be used to determine which section of a yacht's speed record attempt should be used to determine average velocity.

Simulations of GPS position recording and video recording were conducted during a recent record attempt by mounting a GPS receiver and the video camera on the Macquarie team's support powerboat and making three runs along the marked course. Table 1 shows a comparison of the GPS-derived velocity with the video-derived velocity which is a useful means of benchmarking GPS velocity against an approved ISAF/WSSRC technique. In addition, a Kalman filter is used to assess the precision of kinematic GPS positions and verify a simple method of determining approximations to instantaneous velocity from kinematic GPS. Comparing the average velocities derived from GPS observations with those derived from Video Camera observations shows that the average differences for the three courses are 0.017m/s for velocity and -0.026s for time respectively. It is therefore concluded that GPS is a viable alternative to the video camera technique.

3. Science of rowing and athlete tracking

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 2,000m in river, canal or lake-type competition environments in six lanes. To win the competition, atheltes 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; the "B" final determines the next six places (ie 7th to 12th positions). The number of rounds per event depends on the number of crews taking part.

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).

There are 14 different boat classes raced in Olympic rowing. These include eight sculling events in which two oars are used (see Fig. 4a), one in each hand, and six sweep-oared events in which the rowers use one oar with

Table 1 A comparison of velocity and time derived from kinematic GPS and video camera

Course	GPS		Video camera		Differences	
	Velocity (m/s)	Time (seconds)	Velocity (m/s)	Time (seconds)	Velocity (m/s)	Time (seconds)
A3	17.28	28.94	17.30	28.90	0.02	-0.04
A4	17.34	28.83	17.37	28.78	0.03	-0.05
A5	17.30	28.89	17.30	28.90	0.00	0.01

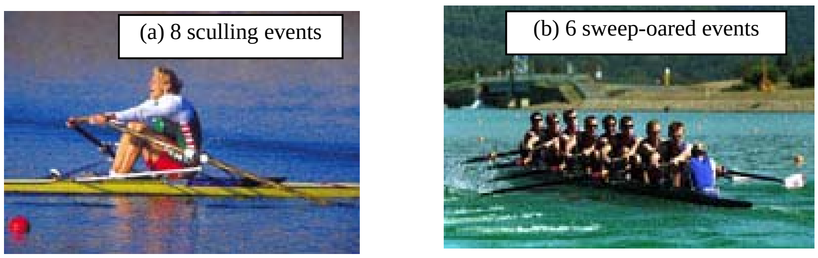

Fig. 4. Sculling (two oars used, one in each hand) and sweep-oared (one oar with both hands) scenarios in Olympic competition (Athens Olympics, 2004)

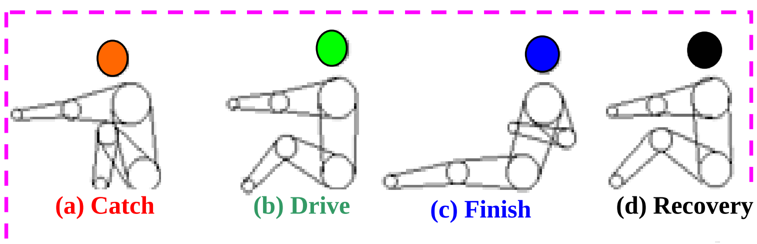

Fig. 5. Schematic diagrams showing the four main sequential phases (ie. a) catch, b) drive, c) finish and d) recovery) in a rowing stroke and the position of head, arm and legs of the rower)

both hands (see Fig. 4b). 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.

The Athens 2004 Olympic Games Rowing events were held at the Schinias Olympic Rowing and Canoeing Centre 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. Forty-five Australian rowers (28 men and 17 women) took part in 11 rowing events.

3.1 Rowing stroke

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-emergence 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 (Mickelson and Hagerman, 1979) (see Fig. 5). These sequential phases must flow from and into each other to produce a continuous and fluid movement.

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) cause balance problems and reduce a boat's speed. The blade must be fully squared to the water at the catch (RowersWorld, 2003).

The boat gains its speed on the drive. In this portion 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 (*ibid*.).

Understanding which movements should occur in each phase of the stroke allows coaches to design effective conditioning programs and evaluate rowing performance effectively. Success in competitive rowing is achieved by taking the shortest time to complete a course (usually 2000m) 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 are: stroke power, stroke length and stroke rate. These factors are important determinants of rowing performance. The stroke power determines how fast the boat travels in a stroke, the length is associated with how far the boat travels in each stroke and the rate is the number of strokes rowed per minute (Seiler, 2003). Therefore the rower must achieve an optimal combination of high stroke power, long stroke length and high stroke rate.

Fig. 6 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.

3.2 Indoor training using ergometer

Fig. 7 shows a typical athlete training procedure in an indoor environment using an ergometer (O'Sullivan and O'Sullivan, 2001). Much of the equipment is either too heavy, expensive, obtrusive or unreliable. Therefore, smart real-time monitoring during training and competition to help elite athletes to improve their performance and avoid injuries is critical for both athletes and coaches. Any methodology that would improve the situation would not only bring benefits to the rower practice, but also to many other sport-related applications including both team sports and individual athletes (eg. Zhang et al., 2003).

A major step forward would be achieved by a comprehensive system that could be used to obtain physiological information of the athlete together with precise movement information through an independent platform which is a low-cost, low-maintenance, miniaturised and integrated sensor system. GPS has been identified as a key element to the success of the project. Such a system is clearly ambitious and will not be achieved in a single step. This project will provide a starting point towards this ultimate goal, through the combination of advanced global navigation satellite systems technology, smart wireless communication, on-line signal processing and GIS, to measure movement information in real-time to a high precision.

4. Development of GPS Based Prototype System

In many sports, it is desirable for movements to be repeated multiple times to obtain a consistent positive result. A greater 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). 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. Physiological information can be relatively easy to obtain using relevant detectors as described above. However, real-time high precision positioning of the athlete has been a challenging task (eg. Fyfe et al., 2001; Hutchings et al., 2000; Larsson, 2003).

A prototype rower tracking system has been developed. Fig. 8 outlines the system architecture and Fig. 9 presents the major phases of the development. Online calculation and a user friendly visualisation mechanism is also integrated into the system.

4.1 Low-cost code GPS

A number of critical factors contribute to the applicability of the GPS system to rowing practice. 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). In spite of the “high-end” geodetic-type receiver providing very high precision results, its disadvantages are the requirements of differential operation, large on-line data processing power and establishment of an independent base station. The cost, volume and weight of this type of GPS receiver and its sophisticated operational procedure unavoidably preclude its practical use.

Because of the challenges of diverse applications and a broadening market, the low-cost GPS has evolved significantly during the past decade (Xiao et al., 2003).

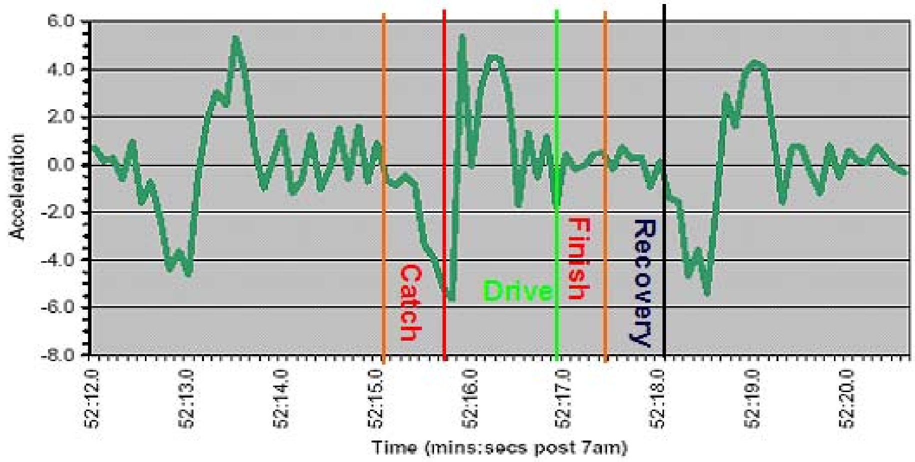

Fig. 6 Schematic rowing stroke signature captured from high precision GPS measurement (Trimble 5700, 10Hz)

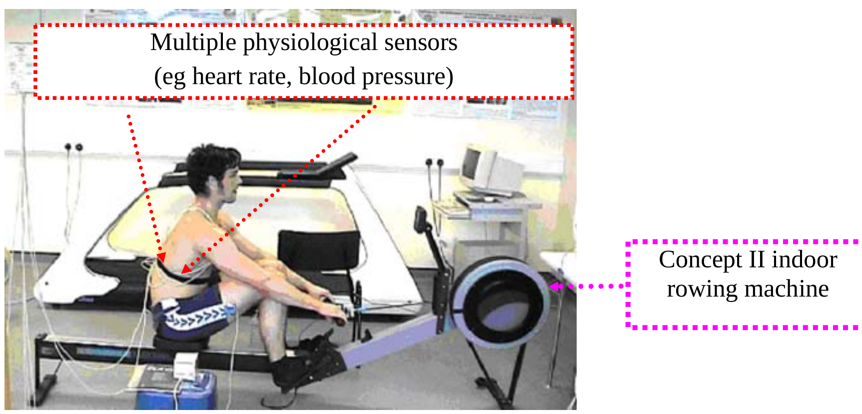

Fig. 7 Typical indoor training instrument (ie. ergometer) and athlete performance and information collection procedure using the concept II indoor device with various physiological sensors attached

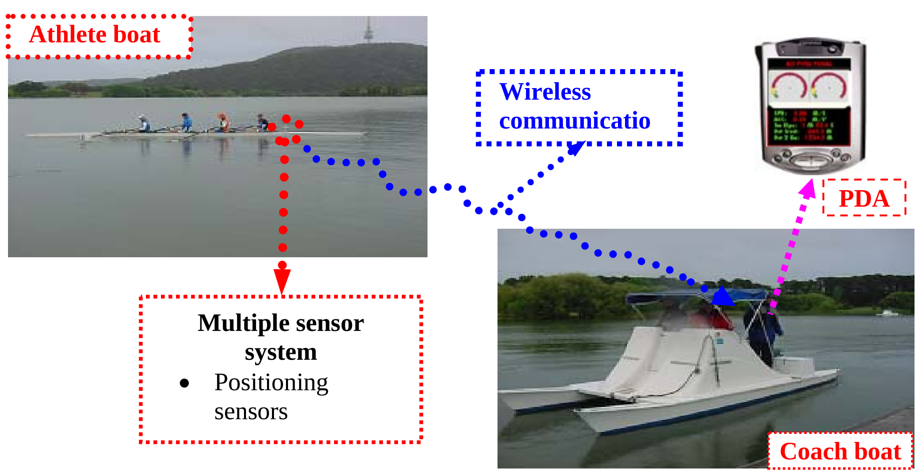

Fig. 8 Skeleton of the system structure of the "smart" rower tracking multi-sensor system with wireless communication and on-line processing functionalities.

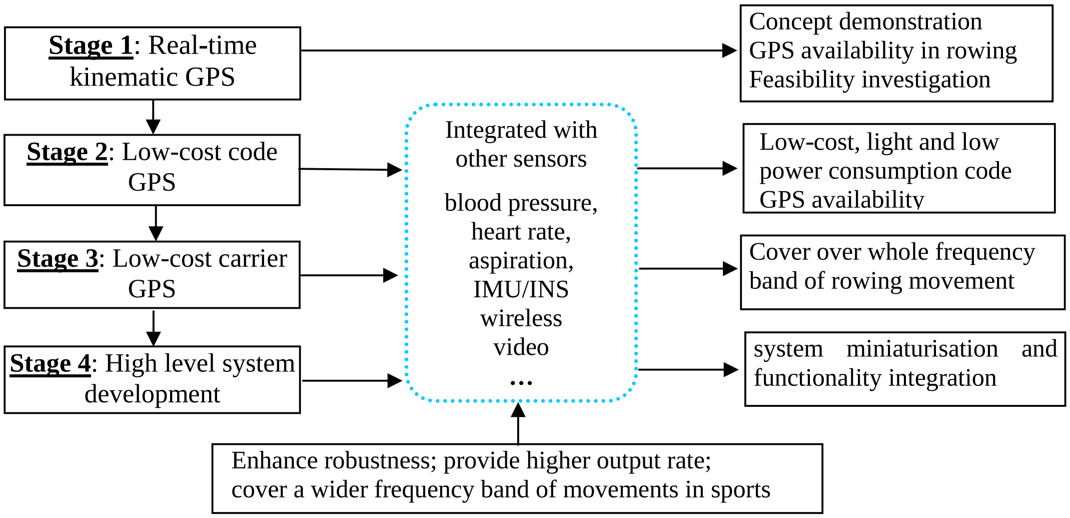

Fig. 9 Development roadmap of the prototype rowing tracking system

Increasingly miniaturised devices have been developed to be wearable and embedded in other devices. Significant new developments of the low-cost GPS units are listed below.

- The ability to process weak GPS signals,
- Combined functionality and integration with other systems such as cellphone or other wireless communication systems (eg. Bluetooth (2003), PDA, and Internet browser),
- Full compatibility incorporating GPS with other devices, and
- Reduction of power consumption, size and weight, and price.

Given these developments, the feasibility of the low-cost, code-only GPS receiver has been investigated and the performance of a low-cost receiver is presented in the next section. A code GPS receiver and a personal digital assistant (PDA) that form the first version of the prototype system are shown in Fig. 10.

4.2 Low-cost carrier GPS

A rower tracking system with the functionality to output PVT information at a rate of 10 Hz has been found necessary and essential in the rowing experiments. In order to develop such a system, a Canadian Marconi Company's (CMC) SuperStar II GPS OEM board is used to form the hardware basis of the system. The SuperStar II can provide PVT solution at a rate up to 5 Hz as well as raw measurements at a maximum rate of 10 Hz. The raw measurements include code phase, carrier phase and signal-to-noise ratio (SNR). Robust algorithms and associated software/firmware have been developed and the current prototype system configuration is shown in Fig. 11(a). The algorithms for PVA solution are developed using a number of special treatments for rowing-specific application. These algorithms have been evaluated through a number of static and kinematic trials as shown in section 5. More rowing trials are on the way and further refinement of algorithms is being undertaken.

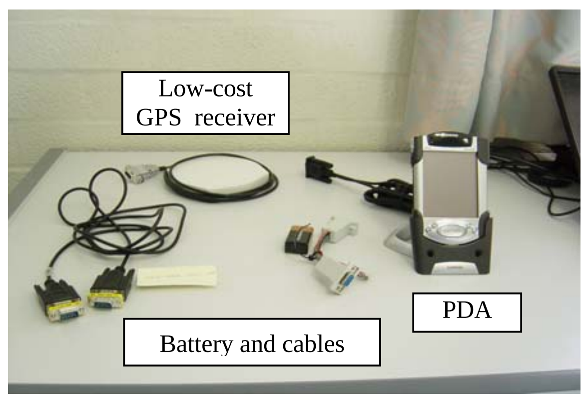

Fig. 10. Configuration of the low-cost code GPS (1Hz) system

5. Field experiments and results

A number of rowing trials have been conducted to assess the performance of both high-end and low-cost GPS systems and to identify potential problems in the river environment. RTK GPS has been proved to be able to provide high precision positioning in a lake environment.

However, there are a number of considerations: multipath effects, signal obstruction, satellite visibility, and obtrusion etc. Ideally the presence of any instrument should not cause direct visual or physical impact on the

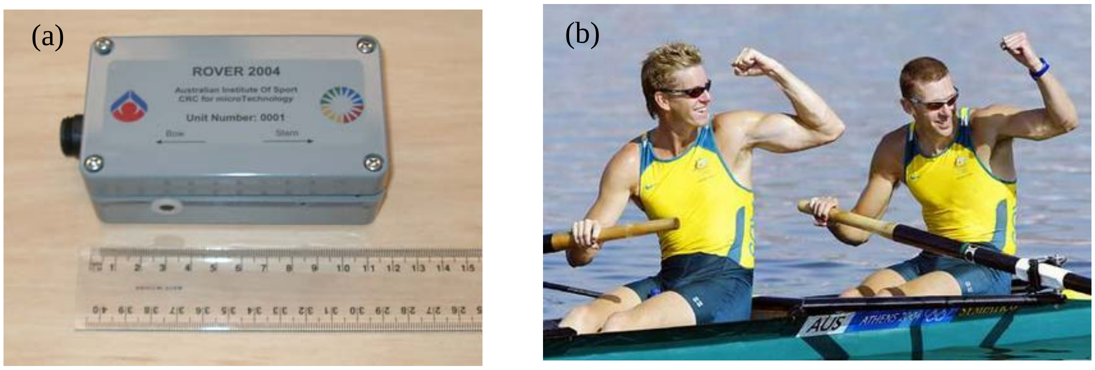

Fig. 11 A compact prototype rower tracking system (a) and photo of James Tomkins and Drew Ginn who won men's pair gold medal (b) in Athens Olympics

athlete. Therefore, the size and height of the antenna is a primary consideration.

The solution from geodetic-type GPS receivers acts as the reference while evaluating the solution of code-only GPS. The base station is located on the bank of a river about ~2km away from the course of the boat trial. The baseline solutions from each of the rowing antennas were processed independently from the base station using the post-processed kinematic technique.

If assuming that the accuracy of the position to one GPS rover is the same as to the other, then, from the simple (Least Squares Adjustment) error propagation law, the accuracy of the position of the kinematic GPS measurement (for a single baseline) can be estimated. A few millimetre accuracy of the antenna height was achieved in a three (consecutive) day trial (Zhang et al., 2003). Given the closeness of the antenna and the reflective nature to the water surface, the performance of the PPK GPS presents consistent results.

An important task of this project was to test the performance of a code GPS receiver which provides low-cost and light weight, less complicated operation, and less communication and storage requirements. Two procedures were used to test the performance of the low-cost GPS receiver: comparison with the high-end GPS receiver and zero motion test of the code GPS receiver (static performance) (Zhang et al., 2003).

Fig. 12 shows the mounting of the two types of GPS receiver (high-end carrier phase Trimble 5700 and low-cost code-only Rojone Genius 1 receivers). Note that the reflective nature of the water surface environment normally causes a high potential multipath effect which could contribute to a large amount of error (upto a few meters for the code GPS receiver). It was expected that elevating the antenna could potentially mitigate multipath effects. Contrary to expectations, the results indicate no significant multipath effects, which will provide guidance for antenna mounting in future trials.

Fig. 13 shows the boat trajectory of the trial for a ~1.5 hour "run". The continuity of the raw GPS measurements and solutions is evident. A close examination indicates that over 99.9% epochs have been resolved with a consistently high level of accuracy.

Fig. 12. RTK geodetic (carrier phase) and low-cost (code-only) GPS receivers mounted on the same boat

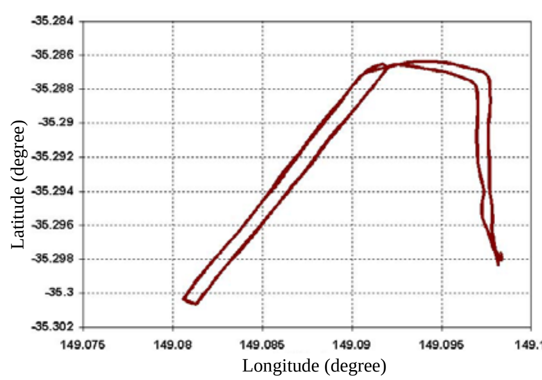

Fig. 13 Boat/rover trajectory obtained from code GPS

6. Conclusions

This paper presents two applications of the GNSS technology in sports: sailing and rowing. Determination of the sailing course at Shallow Inlet for the recent attempt on the World Sailing Speed Record and the feasibility of using GPS technology is described. It is shown that GPS is a superior technology to the current video camera procedure for speed recording. As a result of RMIT Satellite Positioning and Orientation Research Team (SPORT) findings, the Australian team has received World Speed Record Council approval to introduce the method of timing demonstrated in this paper for world record attempts.

This paper also outlines SPORT involvement in the recent development of the CRC for microTechnology Project 2.5. It is demonstrated that low-cost GPS receivers can provide high-accuracy velocity and acceleration information. It shows the feasibility of GPS technology to assist in elite rowing training. It has been demonstrated that the stroke signature captured from GPS is of great value for the investigation of, for example, the duration of the drive and recovery phases, the total time per stroke cycle, drive to recovery ratio, and the relationship of the hands and seat during the drive phase. A number of prototype rower tracking systems have been developed and used by Australian athletes prior to and during the Athens Olympics. Gold was struck twice as Australia came in first in the Men's Quad Skull. Australia snagged three rowing medals (gold, silver and bronze).

It has clearly been shown what can be achieved through "smart" integration of GPS and other advanced technologies for innovative sports applications.

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