

Inertial monitoring of style & accuracy at 10,000 feet

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Abstract

The “*style*” aspect of the parachuting sports of “*style and accuracy*” involves a parachutist diving earthward to gain maximum speed, tucking into a crouch position and performing a sequence of whole body rotations. The scoring of the rotations depends on the overall speed of the performance and the technical purity of the rotations. Given the cost and the 3000m (10,000 foot) altitude location of the style activities, a parachutist practicing style activities has little opportunity for feedback on their training jumps. This paper investigates the usefulness of inertial sensors in the recording, analysis and provision of timely feedback for style activities. Several different sensors were used to collect data at different times. Some trials were collected with triaxial accelerometers coupled with single axis rate-gyroscopes and others with combinations of triaxial accelerometers, gyroscopes and magnetic sensors.

Initial analysis of accelerometer outputs clearly showed key parachuting events such as entering free-fall, arriving at terminal velocity and the parachute opening. Rotations in the horizontal plane and the sequence of rotations were very clear in the gyroscope signal but for rotations in the vertical plane, both accelerometers and gyroscopes contained significant noise. Using triaxial gyroscopes, the vertical rotation became more clearly defined. The existence of tangential and centrifugal acceleration due to the offset between the sensor position and the axis of rotation (Fig.1 c) provided a method of detecting the sensor orientation relative to the axis of rotation as well as determining an estimate of the offset distance. The gyroscope outputs not only provided an easily interpreted record of the turn sequence but other information on the technique such as the performing of an off-axis back loop or the beginning of a back loop while still completing the preceding turn. Additional data is currently being collected with newer devices to develop algorithms to determine the angles of undershoot and overshoot on a turn or back loop and the angle of off-axis rotation.

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Keywords: parachuting; skydiving; style and accuracy; accelerometers; gyroscopes; magnetometers

1. Introduction

Style and Accuracy are two forms of competitive parachuting where competitions for both activities are usually held at a single event, hence the common references to “*Style and Accuracy*”. This paper is only concerned with the style activity. In these style events, the competitors were taken up in an aeroplane to an altitude of 7500 feet. The aeroplane approached the drop zone from a particular direction and on the exit command the parachutist exited the plane and began the descent. The exit, descent and style activities were all monitored by a ground based judges and recorded (Fig.1.b) using a ground based video camera with a high powered zoom lens handled by a skilled camera operator. The requirement for exiting the plane at a particular point insured that all parachutists approached the judges and the camera with the same orientation. After the parachutist had reached terminal velocity they pulled their body

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into a crouch position (Fig.1 a & b) and entered into a sequence of horizontal and vertical rotations consisting of two 360 degree horizontal rotations, a 360 degree backward roll or loop followed by another two horizontal rotations and a back loop. There are four combinations or “series” of rotations and back loops (Table 1) and the parachutist must perform all four series over four different jumps.

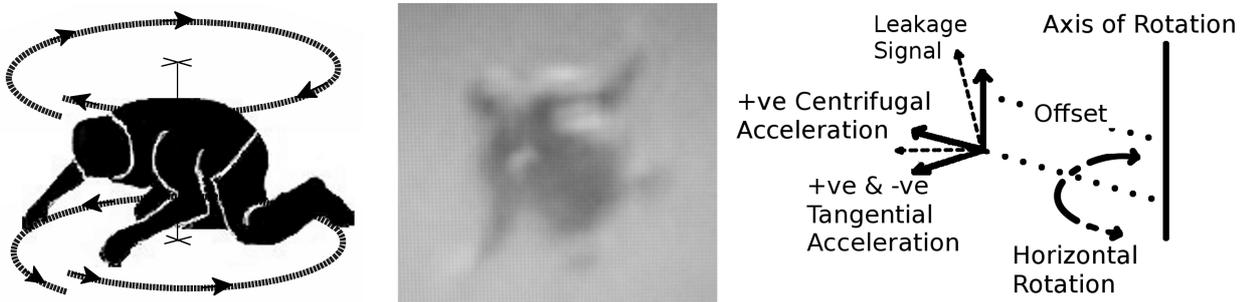


Figure 1 (a) Parachutist in crouching position. (b) Parachutist viewed through camera during descent just prior to beginning style series. (c) Effect of off-axis rotation on triaxial accelerometers including leakage into the vertical axis for off axis sensors. In (b) the knees are tucked tight under chest, much tighter than indicated in (a). Hands provide stability and control the horizontal rotations. Inexperienced athletes tend to unfurl as they perform their loops, slowing their performance.

Table 1. Combinations of style turns and loops

Series Name	Turns and back loop combinations					
Left Set	Left turn	Right turn	Back loop	Repeated		
Right Set	Right turn	Left turn	Back loop	Repeated		
Cross	Left turn	Right turn	Back loop	Right turn	Left turn	Back loop
Reverse Cross	Right turn	Left turn	Back loop	Left turn	Right turn	Back loop

The entire series is timed and at the top international competitive levels, the series will be completed in 6 to 7 seconds. In lower level competitions and with less experienced competitors the series times could extend to 12 or more seconds. The series is assessed on speed and the purity of the turns with various penalties including penalties for undershooting or overshooting on a turn or loop (not stopping “on heading”), or for starting a back loop before completing the previous turn. The full rules are available in [1].

In training activities the parachutist may jump from around 14000 feet to allow time to perform either multiple series or to repetitively practice turns and loops. This could be practice at stopping on heading or improving speed or improving the transitioning between individual turns and loops. For recreational or amateur athletes there is little opportunity for external feedback on their training performance. Ground based monitoring requires an experienced operator and access to a specialized camera and this is not generally available.

Because of their small size, low encumbrance and ability to detect a range of motions, inertial sensors were considered as potential tools for recording and assessing the style activity during training jumps.

2. Procedure

Initially small sensor devices [2] previously used in other sports monitoring [3,4] and consisting of a $\pm 6g$ (gravity) triaxial accelerometer and a single axis of rotation rate gyroscope (150deg/s) were used to capture a number of jumps. After some analysis of this data further data was captured using several of these devices arranged to capture multiple axes of rotation. Later a number of training jumps were captured with a data logger [5] and sensor device [6] combination where the sensor consisted of a $\pm 2g$ triaxial accelerometer, ± 500 deg/s triaxial gyroscope and a triaxial magnetometer.

In each case the triaxial accelerometers were calibrated using a six point calibration technique [7]. The gyroscopes were calibrated by identifying the offset of the device while stationary and for scaling, the devices were rotated for a

set number of turns on a turntable at speeds of 198 deg/s (33rpm), 270 deg/s (45 rpm) and 468 deg/s (78rpm) and the resultant signal integrated to degrees to extract the scaling factor. In this process it was identified that the 150 deg/s device operated well past the rated limits, in some cases continuing to function up to 468 deg/s.

The sensors were located on the chest of the parachutist in a small pouch in the skydiving suit. The pouch was sealable, preventing the device coming out and also constricting the movement of the device during the style activity. This location gave access to the device so it could be turned on and off without interfering with the fitting of the parachutes or the comfort of the individual. The notional alignment of the sensor axes were: “transverse” (across the body and horizontal when standing and when performing style activities), “on-heading” (vertically up when standing but horizontal and outward when performing style activities), and “vertical” (through the body and vertical when performing style activities).

Data was to be collected at as many judged and camera monitored jumps as possible including a ten day National competition and a State competition. Skydiving is a sport that is at the whim of weather and ultimately only two days of the National competition were completed and the State competition concluded without any style competition. Consequently only a small number of assessed jumps were captured along with a number of recreational and practice jumps.

Data was processed using a variety of signal processing tools including filters and transforms. Initially, extracting the orientation of the sensors was attempted using low pass filters[4] and assuming a constant gravitational component once the terminal velocity was reached. This did not appear to be viable as the accelerations and decelerations associated with the style activity, including the varying wind resistance during the back loop, created significant low frequency signal that masked the orientation signal. An alternative technique of extracting the orientation relative to the axis of rotation was developed. This technique was based on the existence of centrifugal and tangential acceleration (Fig.3) due to the offset between the triaxial accelerometer and the axis of rotation (Fig 1.c). By rotating the accelerometer data until all centrifugal acceleration components due to horizontal plane rotations were removed from the notionally vertical accelerometer, the vertical accelerometer became aligned with the actual axis of rotation of the athlete. A similar technique was developed to estimate the offset between the sensor and the axis of rotation by combining the angular velocity and centrifugal acceleration to extract the radius of rotation.

3. Results

Results from collected data were promising in some aspects. Due to the difficulty in actually getting scheduled jumps to occur and the inability to supervise the data collection, some data was of lower quality. The triple-sensor unit, combining accelerometers, gyroscopes and magnetometers suffered a failure on one magnetometer channel and appeared to be only loosely constrained in some trials. Despite this useful data was obtained. The following figures represent examples of data captured from style activities including a timeline of a jump obtained from accelerometry (Fig.2), the triaxial acceleration and single axis gyroscope data for one complete style series showing the centrifugal and tangential acceleration due to off axis rotation (Fig.3), and magnetic sensor output during loops (Fig.4 b).

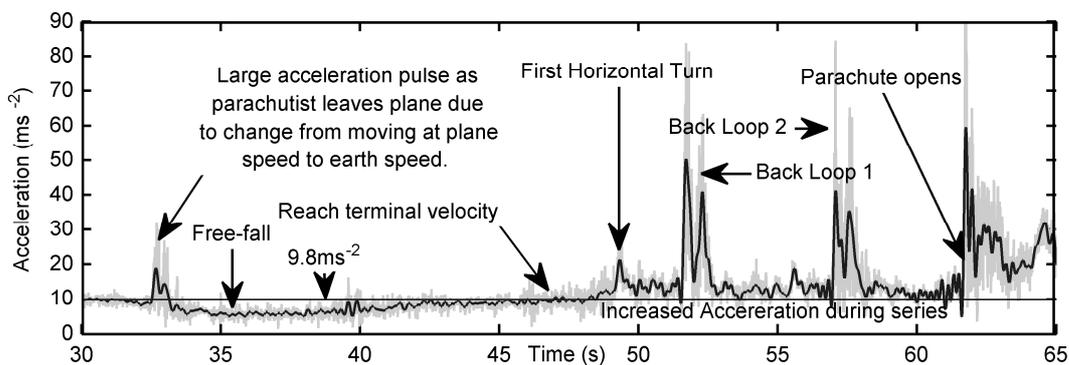


Figure 2 Acceleration magnitude from before the plane exit to after the parachute opening. The grey is raw acceleration and the solid line is the 5Hz low pass filtered signal. This signal gives an overview of the key periods of the activity.

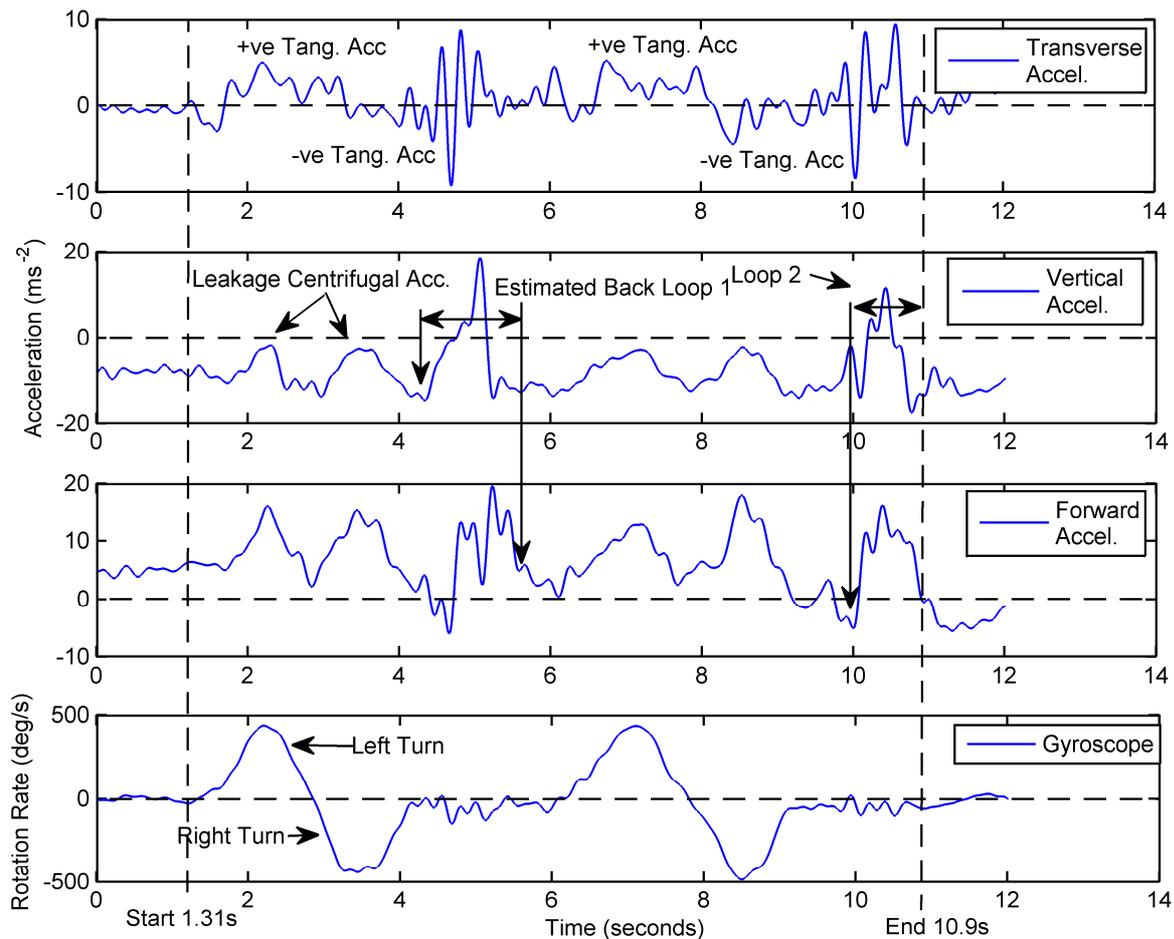


Figure 3. Acceleration and angular velocity for one left-set style series. Data was 5Hz low-pass filtered. Forward tilt of the sensor of approximately 40 deg. caused a significant centrifugal acceleration contribution to the vertical accelerometer. The +ve and -ve tangential acceleration components were not quite balanced due to an alignment error in the horizontal plane (approx. 4 deg.). Theoretically there should be no disturbance in the transverse channel during the back loop but the large signal here suggested an oscillating sideways force, an off axis rotation, movement of the sensor or some combination of these factors. This series was judged as 8.75s

3.1. Timing:

The start timing of the style series was usually clear in the gyroscope data (Fig.3), coinciding with the sudden increase in horizontal rotational velocity. On single axis gyro devices the end of series timing was not as clearly pronounced, having to be estimated from the total acceleration magnitude or clear changes in a particular accelerometer channel as occurred in the forward channel at 10.9 seconds in Fig.3. In each case where judged timing was available, the timing extracted from the sensor device was longer, sometimes considerably longer than the timing given by the judges. Timing differences ranged from 0.3s to 1 second. In all cases, using the start point as indicated in Fig.3, applying the judges timing placed the end point clearly inside the series. Given that the cumulative crystal oscillator errors of the sensor system over short time periods are measured in milliseconds, it suggested that the manual timing underestimated the series duration.

3.2. Device Orientation:

As indicated previously, extracting the sensor orientation from the gravity vector was problematic given the low frequency of the activities, the fluctuating external forces and the overall short period where the athlete held a particular orientation. The alternative method of using the tangential and centrifugal accelerations caused by the offset between the axis of rotation and the sensor location appeared promising. Assuming that the athlete held a steady axis of rotation on the first pair of horizontal rotations the data could be transformed by Euler rotation so that the vertical axis had no centrifugal acceleration components during the horizontal rotations. The sensor data could also be rotated

about the vertical axis so that the tangential acceleration gave both negative and positive results depending on the direction of rotation. For a number of data sets this technique appeared to give satisfactory results, allowing the data to be aligned along the three key axes and with the alignment remaining consistent across the whole series. For some data series, either the athlete completely lost their heading and ability to roll on a single axis or the sensor moved. On a number of occasions this appeared to occur on back loops with the data after the back loop amenable to sensor re-alignment.

3.3. Rotation overshoot and undershoot:

Initially the extraction of angle of rotation from the gyroscope data appeared promising with angles for some style series approximating the judges results within 10 degrees. Later data gave readings consistently large by 40 to 50 degrees, eg readings of 395 to 415 deg. where 350 to 370 deg. might have been expected. Some of these were faster series with higher rotational velocities suggesting that the gyroscope response was non linear at high angular velocity, a reasonable possibility given this gyroscope's specification. It was also difficult to compare the actual readings with video given the small size of the athlete on the screen and the tracking of the camera, sometimes losing the subject at the critical moment.

3.4. Headings from magnetometers.

Despite the failure of one magnetometer channel this technology looked as if it could assist the 'on-heading' detection. The data in Fig.4 is part of a practice jump consisting of three complete left-sets performed continuously. Fig.4 (a) showed that on some occasions the back loops stall and this caused significant noise in both the gyroscope and accelerometer data making it difficult to track the rotations. The magnetometer data for the same back loops showed that the rotations were completed with minimal signal noise. Despite the lack of a third channel the six back loops were clear indicating that they had stayed reasonably close to the vertical plane. Some of the twelve horizontal rotations appear indicating that some of the horizontal rotations strayed out of the horizontal plane; otherwise this would have just formed a darker group of vertical lines near the right axis.

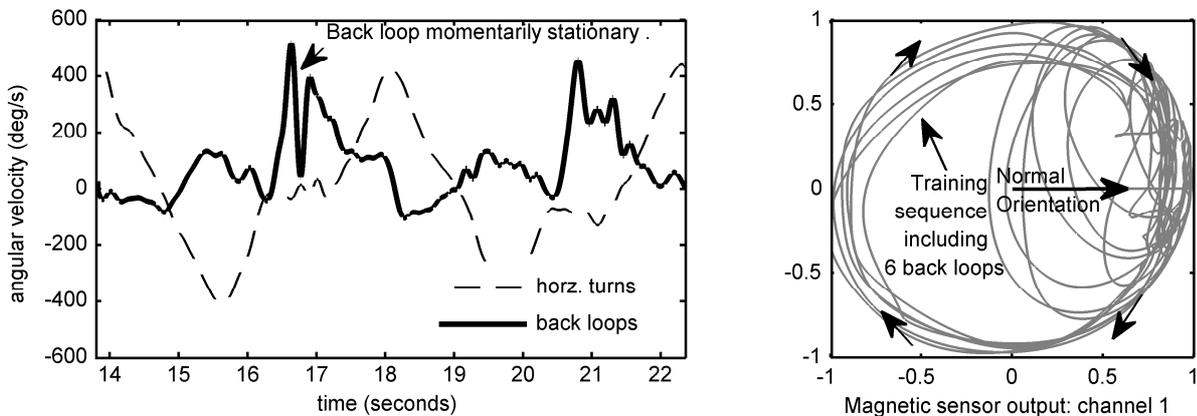


Figure 4 (a) Close up view of gyroscope data for horizontal and vertical rotations. (b) Two-dimensional view of magnetometer data for three contiguous left-sets (12 horizontal and 6 vertical rotations). This captured the changing orientation in the vertical plane. It may help to visualize this as tipped 90 degrees to the right so the orientation arrow points down.

3.5. Gyroscope capture of back loops

The accelerometer data originally captured indicated that accelerations were occurring during back loops that could not be explained by a smooth angular velocity curve like those of the horizontal rotations. Using horizontal angular velocity as a template, attempts were made to reprocess the vertical and forward accelerometer data to remove the centrifugal acceleration due to the back loop. As later indicated by the gyroscope data in Fig.4(a) and from other collected data, the back loop was often not a smooth transition. This was only occasionally visible in the video. This gyroscope data confirmed that the complex accelerations during the back loop were in fact due to complex kinematics.

4. Discussion

This initial research has used some assumptions and qualitative assessments of the available data.

A number of processing steps used were based on assumptions. The main assumption was that the first two horizontal rotations remain in-plane. This assumption may not be fully valid but observation indicated that for most athletes, including the less experienced, while the first two turns might have off-heading issues, the rotational axis was reasonably consistent. During the first horizontal rotations most athletes could hold their body position but the forces during the back loop appeared to ‘unwrap’ many, such that during the second half of the series there was less control over the limbs and over the planes of rotation. This makes it important for future data collection to discount movement of the sensor during the style series. With the forces related to the style activity combined with the wind effects even an apparently firmly located sensor could move around. Rather than modify suits to hold a specific sensor, a possible solution is the use of flat sheet foam rubber or similar cut to tightly fit the small chest pouch. A sensor-sized cutout in the foam would hold the sensor firmly but still allow easy access to the sensor without compromising safety.

A second assumption was that certain recorded accelerations during the sensor orientation process were due to centrifugal and tangential accelerations of an offset sensor and not to other causes^a such as changing wind resistance during the turns or movement in the horizontal plane. This assumption appeared to be valid. Although there were other accelerations occurring the underlying signals matched the signals expected from an offset sensor. It is not assumed that the offset will remain consistent since the unfurling from the crouch position to an extended position will move the centre of gravity and centre of rotation. By assuming that these were sensor offset related accelerations an offset distance could be estimated and then used to remove the centrifugal and tangential accelerations from the horizontal accelerometers using standard equations and the recorded angular velocity.

5. Conclusion

Compared to one and two-dimensional constrained sports monitoring for activities such as rowing and running, the parachuting style activity was a three-dimensional unconstrained activity with none of the traditional inertial sports monitoring reference points of ground contact or pool end turns. In the absence of external references, the initial data collected indicated that by utilizing an offset mounted sensor the data could be self referencing. Despite some sensor problems, each sensor type contributed to the overall picture of the style activity. Accelerometers allowed the orientation of the sensor, gyroscopes captured the horizontal rotations and the magnetometers some of the rotational information. Future work, using more highly controlled data collection protocols and higher specification devices, will focus on combining the timing information, from gyroscopes and accelerometers, with the heading information from magnetometers to extract the heading errors and other stylistic information from the sensor package.

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^a These other causes do exist as the magnitude of the total acceleration during the style series was elevated (Fig.2) indicating that style activity was in someway contributing additional acceleration. Possibly turbulence from the activity was increasing wind resistance and generating an overall deceleration which, when combined with gravity, appeared as an overall increase in the acceleration magnitude. This would need to be confirmed.