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Gyroscopic measurements of the rower's oar pitch angle

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Abstract: - In this paper we present an instrumentation system which integrates inertial motion sensing and mobile computing technologies to acquire sensory information during on-water rowing. The use of miniaturized piezoelectric gyros is proposed and tested to sense the oar rotation. By time-integrating the gyro output signal, the pitch angle, namely the angle the blade is away from perpendicular to the water surface, can be monitored during the stroke cycle.

Timing information about the different phases of the stroke cycle, and the patterns of oar pitch motion during the stroke cycle are presented, in connection with the performance of single sculling trials, in conditions of both slow and fast rowing. The validity of our approach is then discussed, with regard to either the gyro metrological specifications or the idiosyncrasies of the difficult environment where rowing is carried out and gyro measurements are taken.

Key-Words: - Inertial sensing, Rowing, Portable data acquisition, Human performance measurement

1 Introduction

Because of recent advances in their technology of manufacturing, inertial sensors have been receiving significant consideration for applications that are not limited anymore to navigation of aircrafts, robots, and cars; their use is increasingly considered in the analysis of human movement, such as human body motion tracking in virtual reality and augmented reality, personal navigation, and long-term ambulatory monitoring of activities of daily living [1]. Research in the field of inertial sensing of human movement has considered the study of several body parts, including the head, the hands, and the lower limbs [2]-[3]. Sport monitoring can be considered another area of potentially great interest for inertial sensing, although the available literature is still scarce and mostly limited to jogging and running [4]-[5].

In this paper possible applications of inertial sensing are considered in rowing sport activities. Recently, advances in sensing hardware and computer technology have allowed the development of instrumentation systems which provide quantitative information about the rowing technique and its stroke-by-stroke consistency to either the coach or the rower. In all cases, the data-acquisition system to collect the on-water data is housed within the boat. After that all data are converted to a digital format, the on-board computer may telemeter them to a shore or accompanying speedboat computer, for carrying further real-time, or more often, off-line data processing, analysis and visualization [6]-[8]. The on-water acquisition of kinetic information is usually performed with load cells that are integrated within the footboard [8], strain gauge sensors that are mounted on the oarlock [9] or on the oar shaft [10]. The on-water acquisition of kinematical information is usually performed with filming techniques, which allows to analyze the movement of the rower's joints in some detail [6], [11]-[13] and to study the relative timing of the stroke cycle [14]; simple linear and angular potentiometers are also integrated within the boat to measure the seat displacement [10] and the horizontal and vertical angles of the oar [6]-[8], [15]. Another relevant quantity, i.e., the boat speed, is usually measured with speed sensors which are attached external to the shell [8], [10]. Inertial sensing applications in rowing are barely touched, and, mostly, they are considered in the perspective of designing GPS-based navigation systems [16].

In this paper we present an instrumentation system which integrates inertial motion sensing and mobile computing technologies. The system implements a wireless Local Area Network

(WLAN), which includes two palmtop computers (PTC). One PTC is housed into the boat, where it works as both a data-logger and a telemetric unit for data transmission to another PTC, available to the coach. In principle, the coach exploits the collected data and, in turn, he determines how the rower enjoys the information feedback, which can help modify the elements of the stroke that need to be improved. Albeit several sensors, not necessarily inertial sensors, would be integrated in the developed instrumentation system, a single piezoelectric gyro is tested in this paper for its capability of sensing the oar rotation around the longitudinal axis (pitch rotation); the estimation of the blade angle relative to a reference configuration will be obtained by time-integrating the gyro output signal.

2 Method

2.1 The instrumentation system

The part of the instrumentation system housed within the boat is composed of three modules, see Fig. 1: the gyro-board, intended for analog conditioning of the gyro output signal; the sensor control unit – a microcontroller-based board that manages sensor data conversion to digital format and transmission to the on-boat PTC; the on-boat PTC, which is used to send the acquired data to the WLAN, and to report the angular rate time functions and the estimated stroke rate to the rower. The output signal from one piezoelectric gyro (Murata ENC-03J) is submitted to single-stage low-pass analog filtering (cut-off frequency: 20 Hz; amplifier gain: 3.3; sensor sensitivity: 2.2 mV/°/s). Embedded in the sensor control unit, a microcontroller (Microchip PIC 16C774) performs data sampling with 8 quantization bits at f_s = 80 Hz.

The on-boat PTC (Compaq iPAQ H3630), running the MS Windows CE 3.0 operating system, is interfaced to the sensor control unit through a serial communication interface (SCI) at 19,200 b/s. The on-boat PTC, equipped with a radio card (Senao, SL-2011 CD), compliant with the IEEE 802.11b standard, is wirelessly connected with an identical PTC in the hands of the coach – the coach PTC; one additional shore-based computer with the WLAN feature enabled (Acer TravelMate 800) is integrated in the system. Standard TCP/IP communication protocols allow data exchange between the three nodes.

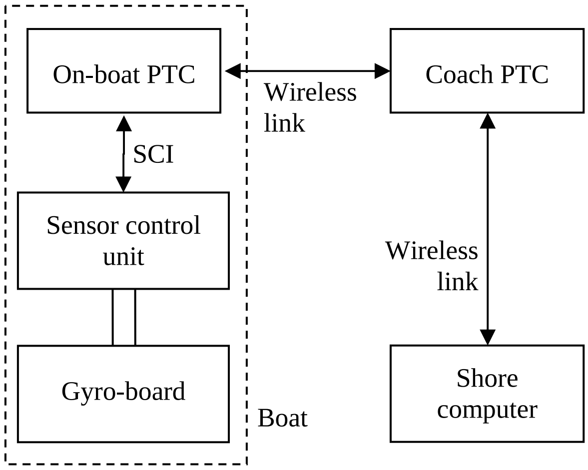

Fig. 1 Block diagram of the instrumentation system.

The system initialization/configuration functions and data visualization are carried by the shore computer through a Graphical User Interface (GUI) written in MS Visual Basic v. 6.0; this node is also used to perform off-line computer-intensive data processing. Alternately, the same functions of initialization/configuration and data visualization can be performed by the GUI running on the coach PCT, which is written in MS eMbedded Visual Basic v. 3.0. The display format for either the stroke rate or the angular rate time functions is identical on both PTC screens, namely. Before the rowing session starts, the rower is allowed to configure the data visualization system, although the settings can be remotely overridden by means of the GUIs running on either the coach PTC or the shore-based computer.

Two data collection modes are implemented: the Sample-and-Send mode, in which the on-boat PTC collects data and transmits them immediately to the other nodes using the wireless link; the Sample-and-Save mode, in which data are collected and stored locally on the on-boat PTC, before performing data exfiltration at the end of the experimental session. In both data collection modes, a time stamp is included for each acquired sample. In the Sample-and-Save mode, data capacity is limited to 100 MB, yielding monitoring times which largely exceed the charge capacity of the PTC battery system.

2.2 Installation and testing

The instrumentation system was installed on a single scull by integrating the gyro-board into the port side oar. After removing the grip of a sculling oar (Dreissighacker, Concept 2) from the adjustable handle, a plastic cap was snugly fitted on the tip of the handle in place of the original end cap. The cap was endowed with a scaffold to which the gyro-board was screwed. Care was taken to align the sensitive axis of the gyroscope along the longitudinal axis of the adjustable handle. The cap was machined with a slot for routing the power and signal wire cable – a flat cable, to reduce its thickness – to the gyro-board from the sensor control unit. Finally, the flat cable was held in place on the outer surface of the adjustable handle and on the shaft, down to the button, by plastic clamps. The flat cable plugged directly into the sensor control unit. Both the sensor control unit and the on-boat PTC were placed within an Aquapac waterproof case, housed over the footboard, within easy viewing distance from the rower.

For system testing, one male senior rower was asked to run a racing scull on a sea-water course in windless conditions, two times at self-selected pace (about 22 strokes/min, i.e., slow sculling), and two times at maximal effort (about 44 strokes/min, i.e., fast sculling). Other experiments were performed by asking the rower to simulate typical errors in squaring the blade (not reported here). No information feedback was available to the rower, the estimated stroke rate apart. The selected operational mode was Sample-and-Send.

2.3 Data processing and reduction

On-line data processing is performed on the on-boat PTC. In the current implementation stage, this processing includes stroke rate estimation by applying a peak detector, which determines the time instant when the peak value of the angular rate occurs during one stroke cycle. Off-line data processing is performed by running code written in Matlab v. 6.5 on the shore computer. Post-processing includes low-pass filtering the gyro output signal via a second-order forward-backward Butterworth filter (cut-off frequency: 10 Hz).

The angular rate time functions are quasi-periodical waveforms, see Fig. 2 for a representative sketch of one stroke cycle (slow sculling). The main features in these waveforms are the presence of one large pulse with positive polarity during finish – counterclockwise rotation, as viewed from the port side – and one generally smaller pulse with negative polarity during catch – clockwise rotation. We propose to identify the recovery and the drive phases in each stroke cycle by identifying the time intervals when the angular rate is almost steady at 0 °/s. The time instant T_{FS} when the finish pulse starts is assumed to represent when the bottom edge of the blade leaves the water; the time instant T_{CE} when the catch pulse ends is assumed to represent the time instant when the blade is placed into the water. Other relevant time events are when the finish pulse ends, i.e., T_{FE} and when the catch pulse starts, i.e., T_{CS}. Thresholding algorithms can be used to perform the segmentation procedure, yielding the estimates of T_{FS}, T_{FE}, T_{CS}, T_{CE}.

Suppose that the initial state is when the rower is ready for the first stroke (drive state). While in the drive state, the algorithm waits for the transition to the finish state, which occurs when $|\omega| > TH_{FS}$ – the corresponding time instant T_{FS} is shown in Fig. 2. While in the finish state, the algorithm waits for the transition to the recovery state, which occurs when $|\omega| < TH_{FE}$, at time instant T_{FE}. While in the recovery state, the algorithm waits for the transition to the catch state, when $|\omega| > TH_{CS}$ at time T_{CS}. Finally, the drive state of the next stroke cycle is entered when $|\omega| < TH_{CE}$ at time T_{CE}. In order to avoid erroneous transitions at the end of either the finish or the catch pulse, the condition that $|\omega| < TH_{FE}$ and $|\omega| < TH_{CE}$ has to be taken for at least four consecutive samples. All threshold values are set to 15 °/s.

The time duration of the finish and catch pulses in the *i*-th stroke cycle are:

$$D_F(i) = T_{FE}(i) - T_{FS}(i)$$
$$D_C(i) = T_{CE}(i) - T_{CS}(i). \quad (1)$$

The temporal interval between two consecutive time events T_{FS} determine the duration D_{SC} of the *i*-th stroke cycle. The time durations D_D and D_R of the drive and recovery phase, respectively, in the *i*-th stroke cycle are:

$$D_D(i) = T_{FS}(i+1) - T_{CE}(i)$$
$$D_R(i) = T_{CE}(i) - T_{FS}(i). \quad (2)$$

Finally, the recovery-drive ratio (*RDR*) in the *i*-th stroke cycle is given by:

$$RDR(i) = \frac{D_R(i)}{D_D(i)}. \quad (3)$$

Albeit the 0% in a normalized stroke cycle is usually when the blades make first contact with the water, our convention that 0% in a normalized stroke cycle occurs when the finish phase starts is due to the sharply rising behavior of the angular rate profile in the initial part of the finish pulse, which helps reduce the uncertainty of the T_{FS} estimate.

The pitch angle is computed as follows

$$\theta(t_k) = INT\left[\int_{TFS}^{t_k} \omega(\tau)\, d\tau\right] + \theta_F \qquad (4)$$

where $INT[\cdot]$ is the rule for numerical approximation to the integral within brackets, e.g., the trapezoidal rule. The upper limit of integration runs from T_{FS} to T_{CE} within each detected stroke cycle. We assume that the initial condition within each stroke cycle is known, which enables to reduce the duration of the time integral to one movement cycle. The pitch angle is then computed from the reference value of the pitch angle at the finish θ_F (θ_F = 3°). An auto-nulling technique is further applied to prevent problems in the computation of the time integral (4). This technique consists of averaging a number of gyro samples when the oar is steady, before the rowing session begins, and subtracting the estimated offset from the angular rate time function [3].

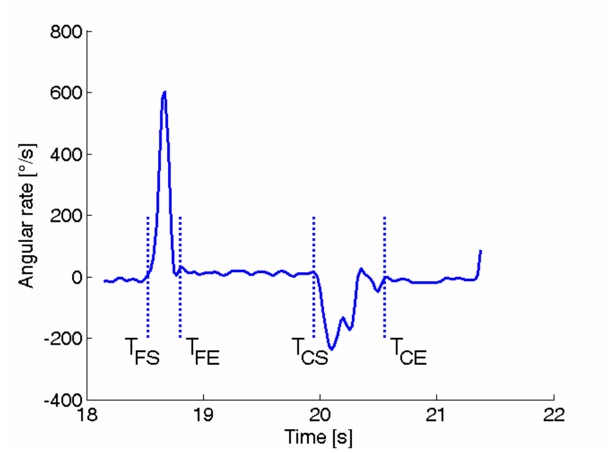

Fig. 2 A representative example of one stroke cycle (slow sculling), with superimposed the occurrences of the temporal events T_{FS}, T_{FE}, T_{CS}, T_{CE}.

3 Results

Figs. 3-4 report the time normalized waveforms of the angular rate and reconstructed pitch angle; to produce these plots, the waveforms are ensemble-averaged across all stroke cycles pertaining to each experimental condition, i.e., slow sculling (Figs. 3a-4a) and fast sculling (Figs. 3b-4b). As for the pitch angle at the catch position of the stroke, we have: θ_C = 4.91° ± 8.15° (slow sculling); θ_C = 4.93° ± 5.45 (fast sculling).

Table 1 reports the measurements (mean ± standard deviation, SD) of D_D, D_R, D_F, D_C, and *RDR*, taken by averaging across the trials for each rowing condition (S: slow; F: fast). Table 2 reports the Pearson's correlation coefficient between D_{SC} and each quantity D_D, D_R, D_F, and D_C.

TABLE 1 Means and SD for the drive duration, the recovery duration, the finish pulse duration, the catch pulse duration, and the recovery-to-drive ratio.

	D_D [s]	D_R [s]	D_F [s]	D_C [s]	*RDR*
S	0.86 0.08	1.79 0.22	0.38 0.09	0.62 0.09	2.11 0.41
F	0.56 0.05	0.79 0.07	0.20 0.02	0.45 0.07	1.40 0.11

TABLE 2 Pearson's correlation coefficient between the drive duration, the recovery duration, the finish pulse duration, the catch pulse duration, respectively, and the stroke cycle duration (**: statistical significance (SS) at $p < 0.01$; ***: SS at $p < 0.001$; ****: SS at $p < 0.0001$).

	D_D	D_R	D_F	D_C
S	0.07	0.82 ****	0.17	0.23
F	0.81 **	0.93 ***	0.38	0.58

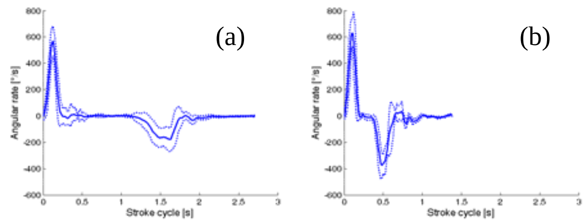

Fig. 3 Time-normalized ensemble-averaged angular rate waveforms – slow sculling (a), and fast sculling (b). Solid line denotes the mean, the dashed curves indicate the mean ± SD.

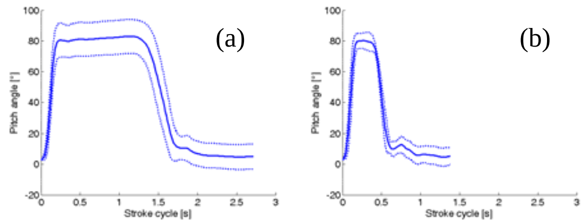

Fig. 4 Time-normalized ensemble-averaged pitch angle waveforms – slow sculling (a), and fast sculling (b). Solid line denotes the mean, the dashed curves indicate the mean ± SD.

4 Discussion

The inspection of the waveforms shown in Fig. 3 reveals that the hand rolling involved in blade squaring (catch pulse) and in blade feathering (finish pulse) is quite fast. As compared with the finish, the hand rolling during the recovery in preparation for the next catch is slower: hence, it takes more time to square the blade, as compared with the time needed to feather the blade.

The estimated values of the pitch angle at catch attest the good overall behavior of the gyro.

The average value of the catch angle is indeed very close to the nominal value from the boat adjustment, with the blade coming to be almost parallel to the water surface during middle recovery. However, the variability of the pitch angle estimate turns out to be relatively large; this variability is actually much higher than the variability resulting from imparting controlled angular rotations to the gyro sensor case during in-use calibration procedures [17-18].

It is difficult to assess to which extent the variability reflects inter-stroke variability of the rower; we believe that a significant part of the variability is due to the shocks and vibrations the gyro is submitted during on-boat trials, especially when randomly occurring contacts of the oar with the sea surface take place during recovery, and when the blade impacts the water during the catch phase. The quite rapid oscillations of angular rate at the end of the catch pulse are believed to be due to the impact of the blade with the water; all these relatively high-frequency noisy components enter the numerical integration routine for pitch angle computation. Their presence also contribute to degrade the accuracy in determining the timing information, especially for the exact moment the blade is dropped into water.

The finish pulse is assumed to correspond, at first approximation, to the transition phase, namely the period, at the beginning of the recovery phase, which precedes the movement of the hands away from the upper body [11]. There, it is shown that the duration of the transition phase is in the interval 0.25-0.22 s (for rowing speeds in the interval 37-41 strokes/min) – in close agreement with our estimate: 0.20 s at 44 strokes/min. As stroke rate increases, the proportion of time spent in the drive phase of the stroke cycle also increases, as shown in Table 1. The average amount of time spent in the drive phase decreases when the rowing rate increases, but not to the extent that time spent in recovery decreases. That is, the increase in stroke rate is accomplished almost exclusively by speeding up the recovery phase of the rowing cycle. In this regard, the results reported in Table 2 show the remarkably high values of the Pearson's correlation coefficient existing between, in particular, D_R and D_{SC}. These data are in good agreement with the conclusions in [14]: the "2:1 advice", i.e., two parts of recovery to one part of drive, may be a good rule of thumb to optimize the run of the boat, but rates either lower or higher than a rate around 28 strokes/min result in proportions that vary systematically from 3:1 to 1:1 as speed increases.

The temporal parameters which characterize the two pulses of angular rate are also subject to change with the rowing conditions: their durations normalized to the stroke cycle duration increase, although the Pearson's correlation coefficient between D_F and D_{SC}, D_C and D_{SC} are not significant, see Tables 1-2. In absolute terms, D_F and D_C decrease with D_{SC}: since the changes in pitch angle are similar in their absolute value during feathering and squaring, the finish pulse is characterized by higher values of angular rate as compared with the catch pulse, see also Fig. 3.

5 Conclusion

In this paper, we have developed an instrumentation system which incorporates inertial motion-sensing and mobile computing technologies.

The interest for the PTC technology is due to the computing and connectivity capacities it may offer at a reasonable cost. An additional interesting feature of PTCs is related to the high quality of their screens, which makes the interaction with the viewing user easy even when the lighting conditions of the outdoor environment are critical. The IEEE802.11b technology is used to wirelessly connect together several computing units within a WLAN, which may also include a laptop computer to perform the computer-intensive computations required by the procedures of data analysis. In implementing the wireless data acquisition system, other radio technologies could be used, e.g., GPRS and UMTS in place of the IEEE802.11b technology; at the present time, however, although longer transmit ranges can be achieved (at the expense of the system's bandwidth), GPRS and UMTS technologies are definitely more expensive than IEEE802.11b technology.

In this paper, we have considered the problem of sensing the oar pitch motion during the stroke cycle by a single piezoelectric gyro. Our preliminary results are promising, in spite that the metrological specifications of the piezoelectric gyro are limited, and the idiosyncrasies of the rowing environment are critical. Because of the low-budget available to our investigation, we had no reference system to provide the ground truth and validate the gyro measurements, e.g., an optoelectronic measurement system; nonetheless, the results of the timing analysis seem to integrate well in the domain of biomechanical knowledge concerning the practice of rowing. Additionally, the patterns of pitch motion of the oar during the stroke cycle are presented here for the first time, yielding some insights into the characteristic signature of blade squaring and feathering.

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References:

[1] A.M. Sabatini, Inertial sensing in biomechanics: a survey of computational techniques bridging motion analysis and personal navigation, *Computational Intelligence for Movement Sciences: Neural Networks, Support Vector Machines and other Emerging Techniques*, R.K. Begg and M. Palaniswami Eds., Idea Group Inc., U.S.A., 2006.

[2] C. Verplaetse, Inertial proprioceptive devices: self-motion-sensing toys and tools, *IBM Systems Journal*, Vol. 35, No. 3-4, 1996, pp. 639-650.

[3] A.M. Sabatini, C. Martelloni, S. Scapellato, and F. Cavallo, Assessment of walking features from foot inertial sensing, *IEEE Trans. Biomed. Eng.*, Vol. 52, No. 3, 2005, pp. 486-494.

[4] R. Herren, A. Sparti, K. Aminian, and Y. Schutz, The prediction of speed and incline in outdoor running in humans using accelerometry, *Med. Sci. Sports Exerc.*, Vol. 31, No. 7, 1999, pp. 1053-1059.

[5] Dynastream Innovations, Inc., Cochrane AB, http://www.dynastream.com/datafiles/SpeedMax%20White%20Paper%20v4_1.pdf

[6] L. Deming, W. Yunde, and S. Jiping, Kinematic and kinetic studies on measurement of rowing technique, *Biomechanics in Sports VI.* E. Kreighbaum, and A. McNeill, Eds., Montana State University, Bozeman, MT, U.S.A., pp. 469-483, 1988.

[7] A. Burnett, B. Elliott, M. Doyle, and B. Gibson, Description of a method to continuously register the hand-curve in rowers, *Biomechanics in Sport XVIII. Proc. 18th Internat. Symp. on Biomechanics in Sport*. Y. Hong and D. Johns Eds., Hong Kong, China, The Chinese University of Hong Kong, pp. 626-29, 2000.

[8] R.M. Smith, and C. Loschner, Biomechanics feedback for rowing, *J. Sports Sci.*, Vol. 20, 2002, pp. 783-91.

[9] F. Celentano, G. Cortili, P.E. Di Prampero, and P. Cerretelli, Mechanical aspects of rowing, *J. Appl. Physiol.*, Vol. 36, No. 6, 1974, pp. 642-47.

[10] A. Baudouin, and D. Hawkins, Investigation of biomechanical factors affecting rowing performance, *J. Biomech.*, Vol. 37, 2004. pp. 969-76.

[11] T.P. Martin, and J.S. Bernfield, Effect of stroke rate on velocity of a rowing shell, *Med. Sci. Sports. Exerc.*, Vol. 12, No. 4, 1980, pp. 250-55.

[12] W.N. Nelson, and C.J. Widule, Kinematic analysis and efficiency estimate of intercollegiate female rowers, *Med. Sci. Sports Exerc.*, Vol. 15, No. 6, 1983, pp. 535-41.

[13] D.H. Lamb, A kinematic comparison of ergometer and on-water rowing, *Am. J. Sports Med.*, Vol. 17, No. 3, 1989, pp. 367-73.

[14] R.G. Dawson, R.J. Lockwood, J.D. Wilson, and G. Freeman, The rowing cycle: sources of variance and invariance in ergometer and on-the-water performance", *J. Mot. Behav.*, Vol. 30, No. 1, 1998, pp. 33-43.

[15] B. Elliott, A. Lyttle, and O. Birkett, The Rowperfect ergometer: a training aid for on-water single scull rowing, *Sports Biomech.*, Vol. 1, No. 2, 2002, pp. 123-134.

[16] K. Zhang, R. Deakin, R. Grenfell, Y. Li, J. Zhang, W.N. Cameron, and D.M. Sikock, GNSS for sports – sailing and rowing perspectives, *J. of Global Positioning Systems*, Vol. 3, No. 1-2, 2004, pp. 280-289.

[17] F. Ferraris, U. Grimaldi, and M. Parvis, Procedure for effortless in-field calibration of three-axis rate gyros and accelerometers, *Sensors and Materials*, Vol. 7, 1995, pp. 311-330.

[18] S. Scapellato, F. Cavallo, C. Martelloni, and A.M. Sabatini, In-use calibration of body-mounted gyroscopes for applications in gait analysis, *Sensors and Actuators, A: Physical*, Vol. 123-124, 2005, pp. 418-422.