HARVESTING TECHNICAL NOTE

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Inertial Measurement Units to Record Operator and Machine Movements

Summary

Common tasks of forestry machine operators on the landing include picking up stems and positioning them, delimbing and processing stems into logs, fleeting logs onto stacks and loading logs onto trucks. All these tasks are under time pressure and must be achieved quickly but also with precision to avoid damaging equipment. The machine operator works at speed and the movements they make are difficult to study. These manual movements are translated to fast movements of the boom, stick and head of the machine. The detailed study of these human and machine movements can be better monitored with inertial measurement units (IMUs). This report outlines the basic principles of IMUs and first use of these devices on human subjects in New Zealand forestry operations.

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Introduction

The number of injury incidents (lost time, medical treatment, and minor injury) has declined over recent years – a trend likely due to greater industry mechanisation (Parker *et al*., 2019). Such technological advances have been a key driver for increasing productivity, safety, and sustainability across the forestry value chain. The Primary Growth Partnership (PGP) programme, *'Te Mahi Ngahere i te Ao Hurihuri – Forestry Work in the Modern Age'*, aims to scale and augment this evolution with pioneering automated systems (FGR, 2018).

As part of the PGP, Scion's Human Factors group has been exploring and extending research that will guide engineering design of new technology to improve productivity, safety, and the operator experience, thereby enhancing human-machine interactions (FGR, 2019).

The productivity, ease of use and suitability of any new technology should be compared with the technology it replaces. It is often difficult to collect useful data from real work situations because the presence of the researcher can disturb the normal flow of work. Furthermore, high risk workplaces can introduce unacceptable hazards to participants and researchers alike. An example is observing excavator-based processing and loading machines. In tasks like these, unobtrusive data collection methods are required. These methods must be relatively inexpensive, simple to administer and provide data in a form that is easily analysed.

Kirwan & Ainsworth (1992) identified three levels of intrusion on a participant by researchers. The lowest intrusion level, 'observer unobserved', uses sensors to record activity. The researcher is completely removed from the workplace.

Excavator-based machines are used on landing operations in forestry because they have the power to lift logs weighing up to two tonnes and can reach in any direction (Figure 1).

Figure 1: Excavator based log loader

The excavator boom has an extension reach of over five metres and the power to easily carry a processor head to delimb and cut logs and move those logs onto stacks or to load trucks. The body of the excavator is mounted on a rotating base

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attached to the tracks. Skilled operators can move all five degrees of freedom at once – rotate base, lift boom, extend boom, open/close and rotate grapple. This considerable flexibility makes the study and recording of machine, and operator movements extremely challenging.

Measuring the detailed movement of boom mounted forestry machines (La Hera & Morales, 2019) and construction machines (Rashid & Louis, 2020) using sensors is an active area of research. Reasons for study include increasing productivity, reducing time and cost of operations. Ultimately the detailed understanding of boom movement can be used to develop semi-automation and full automation (La Hera *et al*., 2021).

Scion's Human Factors group wanted to record the hand and arm movements of machine operators and the corresponding movements of the forestry machines themselves to better understand the difference between skilled and novice operators and determine the workload of machine operators. Forestry machine operation may one day be automated and/or performed by robot technology that will need to replicate the decision making of human operators.

Inertial measurement units (IMUs) are the standard method for measuring and recording movements of people and machines.

Inertial Measurement Units

IMUs are comprised of three measurement tools that can capture data about the unit's movement. The tools are 3D accelerometers, 3D gyroscopes and 3D magnetometers (Figure 2).

- 3D accelerometers consist of a mass-spring system contained within a vacuum. When the unit moves the mass is displaced and the displacement is measured.
- 3D gyroscopes measure the orientation of the unit about one plane and rate of turning (angular velocity). A tiny oscillating mass is suspended on a spring system which senses orientation and angular velocity.
- 3D magnetometers measure the direction and strength of a magnetic field however they are prone to error due to magnetic distortions from nearby metallic objects.

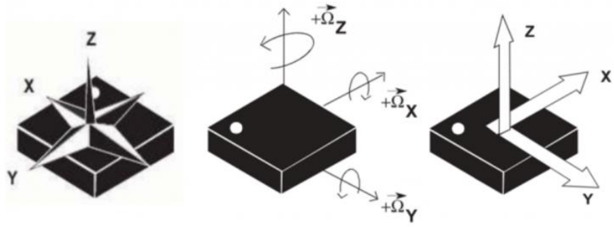

Figure 2: Axis orientations of (from the left) magnetic, gyroscopic and acceleration elements of the IMU providing a total of 9 degrees of freedom (Sparkfun).

Short term changes in orientation of the IMU are accurately tracked by the gyroscope but accuracy reduces over time. Adding signals from the accelerometer and magnetometer provides long term stability (Roetenberg *et al*., 2009). However, if measuring the movement of metal parts, such as an excavator boom, the magnetic field of the surroundings must be adjusted for in the IMU calibration. Magnetic field mapping is a standard procedure to 3D calibrate the IMU.

Xsens DOT IMUs were selected for this study because of their low cost and flexibility of operation. The distributor also provided considerable backup with advice and training. The IMUs are small and lightweight and can be worn on the body or attached to machinery (Figure 3).

Figure 3: Xsens IMUs and strap to hold IMU on an arm, leg or machinery part

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However, the user must learn how to implement the IMUs correctly to collect useful data.

Visualisation of movement

The IMUs on their own can record data but it can only be visualised as plots of movement in the x, y and z axes against time and displayed on a smartphone with the Xsens application (Figure 4). Also, the movement of multiple IMUs is difficult to interpret from a line plot.

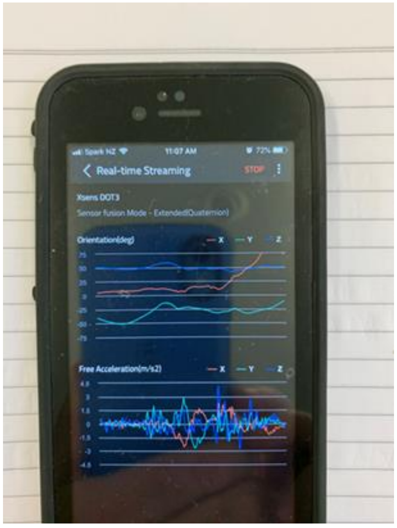

Figure 4: Line plot from individual IMU. Three lines correspond to movement in the X, Y & Z axes. Top plot is orientation and bottom plot is acceleration.

To handle multiple IMUs and make the data visual, the application KineXYZ has been developed. KineXYZ is a '3D development platform' to communicate with the Xsens DOT IMUs, record their motion and display the movements of the IMUs in real time in a cartoon like 'kinematic modeller'. The kinematic modeller allows a combination of jointed elements to be created such as forearm and upper arm or excavator boom and stick. KineXYZ requires an iPad to run the application and link to the IMUs.

Method

IMUs are very precise scientific instruments and must be calibrated before each use to ensure they are measuring accurately and that they are all orientated in the same way in three dimensions.

It was simplest to gain experience with IMUs by attaching them to a person to understand how to collect useful data. Initially we attached one calibrated IMU to the forearm of a machine operator of a Caterpillar grapple loader and collected data, which was displayed on a smartphone. We then increased the number of IMUs to four – both forearms and upper arms of a person in an office environment where we had more control.

To record multiple IMUs, they must be connected by Bluetooth to the KineXYZ application on an iPad. KineXYZ which records the data and allows the researcher to link the correct IMU to the correct body (or machine) segment. In this way a virtual kinetic (moving) model of the body or machine can be created.

Results

Orientation and acceleration of a single IMU mounted on the forearm of an excavator-based log loader was recorded over 15 minutes. The output was displayed on a smart phone (Figure 4).

Subsequently, on advice of the Xsens distributors the KineXYZ application was loaded onto an iPad to better interpret the data. Xsens also provided Scion with biomechanics course material using the Xsens DOT and KineXYZ (Konrath, 2020). Under the guidance of Xsens kinematic models of two linked IMUs representing the boom of an excavator were built. The movement of two IMUs is represented on the KineXYZ application window (Figure 5).

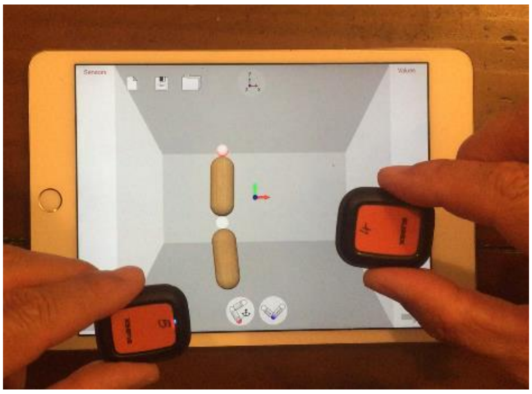

Figure 5: KineXYZ display of two IMUs.

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In Figure 5, the connection between the two IMUs is represented on the screen as two segments linked by a joint in the middle. The uppermost end of the top segment is anchored. Each of the two brown rods on the screen is linked to a corresponding orange IMU. As the IMUs are rotated or moved the linked rods move on the screen in the same direction, speed, and orientation (Figure 6). Up to five IMUs can be used at one time.

Figure 6: Right IMU (upper segment) rotated and the left IMU (lower segment) held motionless.

Four IMUs were attached to a test subject (Figure 7). The black bands are straps holding the IMU devices securely on the subject's arms.

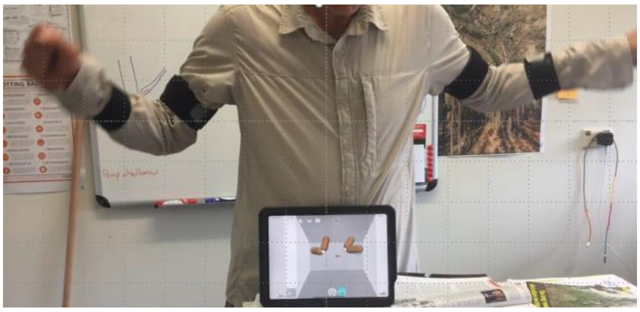

Figure 7: Four IMUs attached to upper arms and forearms and four corresponding segments move in unison on the display.

IMUs can be connected to the moving parts of an excavator boom and their movement represented on KineXYZ. Angles and acceleration of individual elements (boom, stick) are also calculated by KineXYZ.

Discussion

Forestry machines and their operators work at a high tempo. Hand movements are repetitive and quick and so are the corresponding movements of the controlled forestry machine.

The IMU is an unobtrusive proxy for a researcher sitting on the landing watching and recording every movement of the machine and operator.

Simple observation of machine operators does not result in an understanding of why operators use the machine the way they do. The presence of an observer in the cab or on the landing would have compromised data integrity by disrupting the normal flow of work of the operator. The presence of the observer also results in the operator feeling 'watched' and therefore pressured to perform either at a higher rate of work or at a higher level of skill than normal.

There has been a steep learning curve to understand how to use IMUs to collect useable data. The Xsens DOT IMUs are inexpensive but are not an 'off the shelf' solution. They require the user to invest considerable time learning how to set up the devices, account for sources of error and collect, display and interpret output on an after-market application – KineXYZ.

Now that Scion's Human Factors programme of the Automation and Robotics PGP has developed this capability in IMU use, although novice at this stage, studies can be designed to make full use of IMU capabilities. The alternative would be to hire in expertise in IMUs at considerable cost and having to escort them to forest operations – doubling research personnel and costs.

Next steps

IMUs will be attached to the boom, stick and other appropriate parts of an excavator (Figure 8). Concurrently the machine will be videoed, and a task analysis of movements created in the Behavioral Observation Research Interactive Software – BORIS (Friard & Gamba 2016). The task analysis and IMU kinematic analysis will be compared. Published studies give us confidence that machine movements can be identified accurately and efficiently (La Hera & Morales, 2019; Rashid & Louis, 2020).

Figure 8: IMU locations to record the moment of boom and stick of an excavator (Rashid & Louis, 2020).

Conclusions

IMUs provide human factors researchers with a comprehensive tool to record the movement of humans and machines in congested and hazardous environments. To date the movement of people in a laboratory environment has been recorded successfully. The next stage is to attach IMUs to forestry machine operators to gain a comprehensive understanding of arm and upper body movements to determine the workload of machine operators. The IMUs will then be attached to the moving elements of forestry machines such as the boom, stick, and grapple or processor head to record those movements.

This study is part of a long-term programme, with much more work to be done in collaboration and partnership with sector stakeholders, researchers and innovators, and technology developers and manufacturers, to reduce machine operator workload and understand the impact of automation on the human operator. Such collaboration is a key element of the PGP programme and will guide the effective use and adoption of new technology across the New Zealand forest industry.

References

FGR, (2018). Primary Growth Partnership Business Case “Te Mahi Ngahere I te Ao Hurihuri – Forestry Work in the Modern Age”. Business case prepared for the Ministry for Primary Industries. Forest Growers Research Ltd, 30 September 2018.

FGR, (2019). Forest Growers Research Primary Growth Partnership Annual Plan 2019 – 2020. Forest Growers Research Ltd, 30 August 2019.

Friard, O., & Gamba, M. (2016). BORIS: a free, versatile open-source event-logging software for video/audio coding and live observations. Methods in Ecology and Evolution 7(11), 1325-1330.

Kirwan, B., & Ainsworth, L. K. (1992). A Guide to Task Analysis (1st ed.): Taylor & Francis.

Konrath, J (2020). Wearable technology in biomechanics and S.T.E.M. education. Xsens Technologies B.V. The Netherlands.

La Hera, P. and Morales, D. (2019). What do we observe when we equip a forestry crane with motion sensors? Croatian Journal of Forest Engineering. 40(2): 259-280.

La Hera, P.; Morales, D. & Mendoza-Trejo, O. (2021). A study case of dynamic motion primitives as a motion planning method to automate the work of forestry cranes. Computers in electronics in agriculture 183.

Parker, R., Hooper, B., Dodunski, C. & Raymond, K. 2019. Harvesting Landing-based Injuries: Analysis of IRIS data. Harvesting Technical Note HTN12-02. Forest Growers Research Ltd, Rotorua, New Zealand. 9p.

https://learn.sparkfun.com/tutorials/lsm9ds1-breakout-hookup-guide/all Accessed 1 May 2021.

Rashid, K. & Louis, J. (2020). Automated activity identification for construction equipment using motion data from articulated members. Frontiers in built environment 5, article 144.

Roetenberg, D., Luinge, H. & Slycke, P. (2009). Xsens MVN: full 6DOF human motion tracking using miniature inertial sensors. Xsens Motion Techol. BV, Technology Report.