Center of Gravity Tracker for Operator Fatigue Detection

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Abstract— **Driver fatigue is a cause of serious accidents for heavy machinery operators. Monitoring operator position, as indicated by their Center of Gravity (CoG), may be a means to non-invasively detect driver fatigue. We prototyped a research tool that tracks CoG from four sensors located within the legs of a seat, and validated its accuracy and precision. Our primary contributions are the development of a low-cost integrated CoG detector for seated drivers and the design of a flexure structure to protect load cells from shocks, tensile and shear forces. This system will enable research into CoG as an indicator of fatigue.**

I. INTRODUCTION

It's estimated that at least 100,000 motor vehicle crashes in the USA alone are the direct result of driver fatigue each year and this particularly true in the road transport and construction industries [1]. Fatigued heavy machine operators exhibit significantly reduced decision-making capabilities and perception [2]. For these reasons, a system that actively monitors and measures operators' fatigue level is essential.

Several methods, such as electromyography, pelvis position and eye tracking, have been explored for fatigue detection [3] [4]. One popular method is PERCLOS (Percentage of Eyelid Closure Over the Pupil Time), which is calculated by counting the number of frames in which there was no pupil detected and dividing this by the total number of frames for a specific time interval, has been shown effective with air traffic controllers [5]. The most basic form of fatigue measurement that doesn't require any additional technology is through self-reporting. This can introduce bias, but also allows for an honest evaluation of the perceived capabilities of each individual [6]. Many of the more quantitative measurements of fatigue require sensors that could be undesirable for operators. Drivers do not want to attach electrodes (EMG or EEG) and unions do not want their members to be recorded while working. There is a need for non-invasive fatigue detection technologies.

Several studies indicate that the driver's CoG is a promising metric for fatigue detection. Unlike other technologies, CoG sensors can provide useful data without disturbing drivers. Furugori et al. showed that change in CoG is correlated with change in posture and seating position, and developed a fatigue detection algorithm for use with CoG data [7]. Nagasaku et al. found that the frequency of body movements correlates with the length of time that drivers' eyes are closed [8].

Medical and industrial sensors currently exist to measure the CoG of a person or object. In the doctor's office, AMTI and Midot force plates are used to measure center of pressure for posture treatment and biomechanical research. These are large, heavy, and rigid, but deliver high accuracy (CoG position within 0.2 mm). Consumer products, such as the Wii Balance Board, have been proposed as alternatives to expensive force plates in medical applications, but cannot handle large loads [9]. In industry, systems from Resonic are used to identify the CoG and moments of inertia for large vehicles and spacecraft weighing thousands of kilograms. The accuracy, load rating, and cost of existing medical and industrial products are not suited to monitoring a seated operator.

In a previous study, Sumitomo Heavy Industries (SHI) tested a commercially available pressure pad, consisting of a uniform grid of pressure sensors, placed on top of a seat to measure CoG. While thin and flexible, it is expensive and over articulated for CoG measurement. In this paper we present the proof-of-concept of a robust CoG sensor specifically designed for use with seated operators and vehicle integration.

II. DESIGN APPROACH

A. Functional Requirements

Considering the application and in reviewing prior art the following design requirements were identified:

- **Accuracy:** Detect CoG with an absolute accuracy of better than +/- 2 mm in X and Y.
- **Robustness:** Survive worst-case loading forces from a 280 lb driver operating the machine on a slope.
- **Output:** Record CoG faster than 5 Hz. Raw readings and time-stamps should be recorded as well as CoG.
- **Input:** Operate on 12 V or 24 V DC input from vehicle batteries / power systems.
- **Cost:** While research focused, the design should suggest a path towards commercialization and not involve exotic processes or materials.

B. System Architecture

The system takes inspiration from consumer (bathroom) weighing scales, which typically have four flexure-based load

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cells, one located at each corner of a frame. Our design, integrates custom designed load cell assemblies into each of the four bolt points that secure the top of the seat to the lower suspension unit, as shown in Figure 1. This will enable easy test installation.

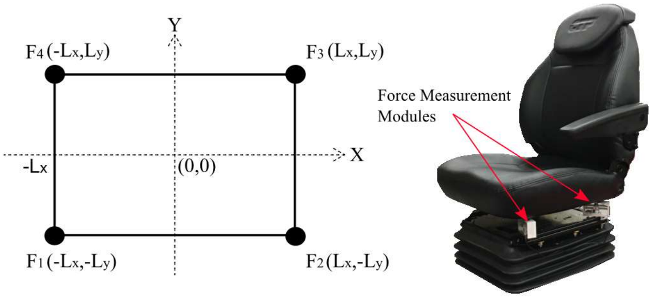


Figure 1: Forces on four legs of the seat are measured to estimate CoG.

If the driver's CoG (accounting for tilt and CoG height) is located within the rectangle defined by the load cell positions, each cell will be placed into compression. The sensor system must measure compressive forces at each corner, yet survive high tensile and shear forces, not experienced by traditional scales. With this design the CoG is expressed by Equations 1.

$$
\begin{aligned}
x &= \frac{-F_1L_x - F_4L_x + F_2L_x + F_3L_x}{F_1 + F_2 + F_3 + F_4} \\
y &= \frac{-F_1L_y - F_2L_y + F_3L_y + F_4L_y}{F_1 + F_2 + F_3 + F_4}
\end{aligned}
\qquad (1)
$$

Each load cell's output voltage (V_i) is a function of the applied force (F_i), excitation voltage (V_s), rated output (k), and capacity (F_{max}).

$$
V_i = V_s k \frac{F_i}{F_{max}} \qquad (2)
$$

V_i is amplified by an instrumentation amplifier and read by a 24 bit ADC. The reading from the ADC can be written as

$$
\alpha_i = 2^{24} \frac{V_i - V_{r-min}}{V_r} \qquad (3)
$$

where V_{r-min} is the minimum voltage that the ADC can read (0 volts for a one-sided ADC) and V_r is the total range of the ADC. Finally, the CoG location is estimated from the four load cell readings.

$$
\begin{aligned}
\hat{x} &= \frac{-\alpha_1L_x - \alpha_4L_x + \alpha_2L_x + \alpha_3L_x}{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4} \\
\hat{y} &= \frac{-\alpha_1L_y - \alpha_2L_y + \alpha_3L_y + \alpha_4L_y}{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4}.
\end{aligned}
\qquad (4)
$$

The accuracy of the CoG measurement is limited by the linearity and precision of the load cells and sensing electronics as well as load cell placement, but not by the absolute accuracy of the sensors. The uncertainty of the CoG estimation in x can be expressed as a function of uncertainty in force measurement (U_{α_i}) and uncertainty in load cell placement (U_{L_x}) by Equation 5. This equation holds for the y direction as well.

$$
|U_{\hat{x}}| = \sum_{i=1}^{4} \frac{\partial\, \hat{x}}{\partial\, \alpha_i} U_{\alpha_i} + \frac{\partial\, \hat{x}}{\partial\, L_x} U_{L_x} \qquad (5)
$$

With $\mathrm{L_x} = 300\, mm$, and $U_{L_x} = 1\, mm$, a total force of 1000N a 1% accurate load cell (linearity error) the worst case accuracy of CoG limit is ±4mm.

III. DETAILED DESIGN

A. *Flexure design for load cell*

To minimize cost, a COTS uniaxial compression-only type load cell was used. A flexural support block was constructed to isolate the load cell from shear and tensile forces, without hindering the measurement of compressive forces. Figure 2 shows the flexure design and Figure 3 shows the load paths within the flexure. Inside the block is a ~$60 200kg, IP66 load cell (TAS606, HT Sensor Technology Co).

Compression forces from the seat are directly communicated through the setscrew into the load cell. Since the flexures are ~1,000 times less stiff than the load cell vertically, the parasitic vertical load they carry is negligible. Tensile loads cause the nut assembly to move upwards and bottom out on the aluminum structure. Shear loads are carried from the setscrew to the blade flexures and then into the structure. The system is preloaded with a Belleville washer to prevent separation and impact from damaging the load cell. The low-taper, abrasive-waterjet cut 1" thick aluminum plate creates deep flexures with resistance to shear in all directions.

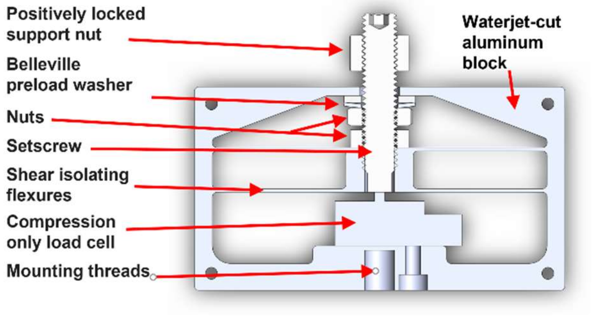
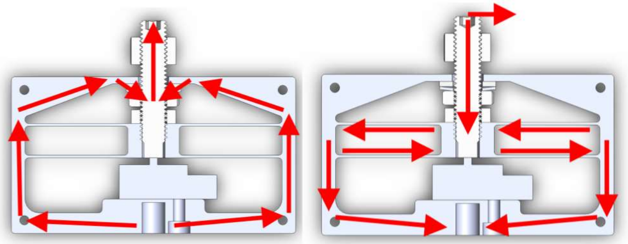


Figure 2: Flexure design to transmit axial loading to the load cell.



(a) Tension

(b) Shear

Figure 3: Deflection of tensile and shear forces through the flexure.

The expected forces exerted on each load cell were calculated for a typical weight and CoG height of a seat and operator with the machine located on a slope. Shown in Figure 4, this analysis was used to determine a maximum compression load of 1500 N, tensile load of 922 N and shear load of 200 N in all directions. Since loading is heavily dependent on the CoG height of the operator, the modules are located between the seat base and its suspension.

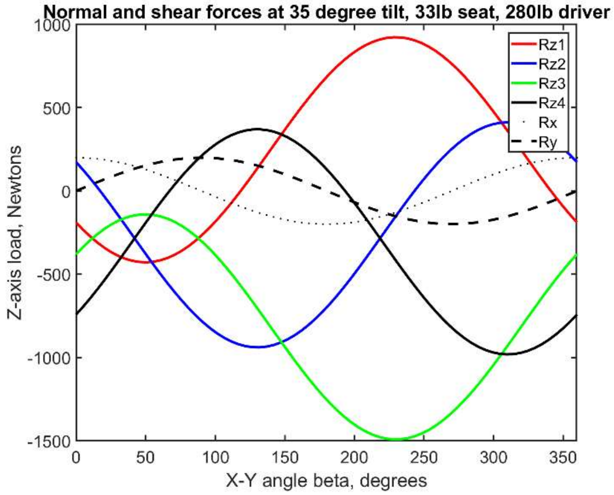


Figure 4: Simulated vertical forces on the 4 measurement modules (Rz1, Rz2, Rz3, Rz4) and shear forces (Rx, Ry), with the machine positioned on a 35º slope and considering the driver and seat weight, as function of cab/machine rotation angle (beta).

B. *Sensing Electronics*

The analog output of a load cell is typically on the order of mV. This delicate signal needs to be amplified and digitized before the CoG location can be determined. We used a HX711 Module, (a 24 bit ADC with a PGA) to amplify the output and an Arduino Mega to process the data and record CoG location.

While the accuracy of the device is limited by the uncertainty of the load cells, the sensing electronics linearity, and the placement accuracy, the resolution is limited by noise. Electrical and magnetic fields common in an automotive environment can induce noise on the analog output of the load cells. The noise level of the system was analyzed and is presented in the testing section.

C. *User Interface*

An LCD screen provides a visual display of CoG location and allows users to easily confirm whether the device is functioning. Three buttons - Start, Save, and Zero - control the device. When the Start button is pressed, the microcontroller creates a new .csv file and starts recording time and raw load cell readings. When the Save button is pressed, the microcontroller stops recording the data and saves the csv file onto a micro SD card. When the Zero button is pressed, the microcontroller applies an offset to the load cell readings to reset the location of the CoG to zero along both axes. Zeroing can be performed before an operator sits on the seat to reject the influence of the seat in CoG estimation. The system also provides data streaming from a USB port when a user needs to process CoG data in real time.

D. *Fabrication*

Figure 5 shows the diagram of the overall system. We designed a PCB to connect the load cell inputs, amplifiers, and computation into a single physically robust and noise resistant unit. Figure 6 shows the plastic box which encloses the prototype electrical system. Shielded wires connect each load cell to the enclosure.

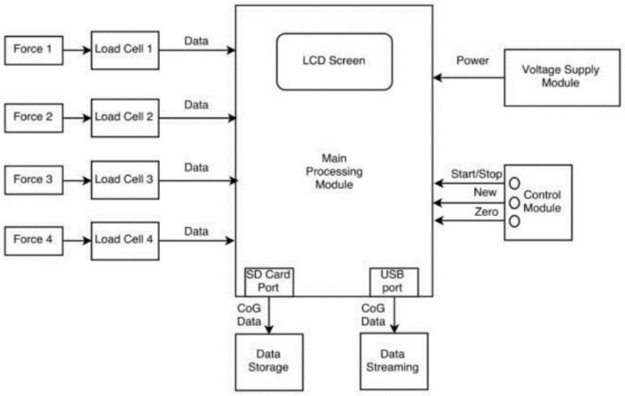


Figure 5: Diagram of integrated system's electronics.

Figure 6: Integrated System with a PCB enclosed in a box.

IV. TESTING & RESULTS

We conducted two laboratory tests to analyze the system's resolution and accuracy:

In the first test, we measured resolution by determining the static noise level. We placed a 100lb weight on the seat and recording the CoG position for 2 minutes. The standard deviation of the CoG position was 0.059 mm (X) and 0.029mm (Y). The peak to peak deviation of the CoG position was 0.36 mm (X) and 0.17mm (Y). This test, shown in Figure 7, demonstrates that system-level noise is sufficiently low to achieve the target resolution and accuracy.

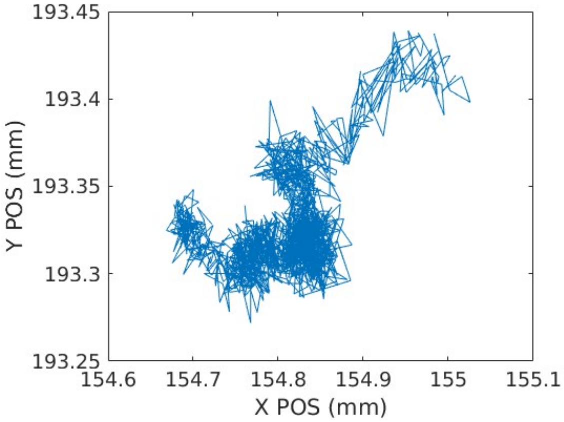


Figure 7: Static noise level with 100lb weight.

In the second test, we applied a concentrated load on the points of a 4 by 3 grid, where the points were separated by 75 mm horizontally and 50 mm vertically. Figure 8 shows the input grid and processed CoG estimations. The average error between the measured and actual points was 3.9 mm, however displacement errors on the order of 10 mm were seen.

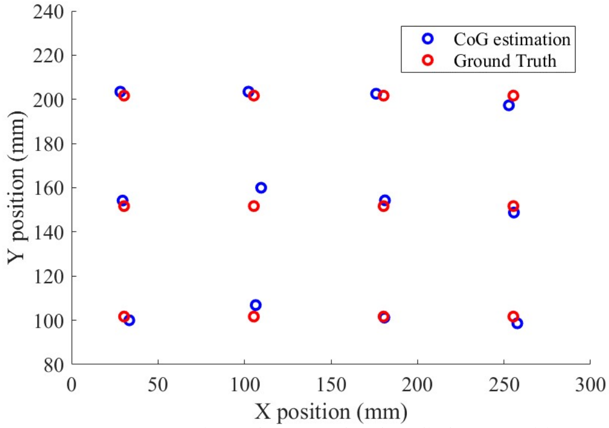


Figure 8: Comparison of measured and applied CoG position.

V. CONCLUSION & FUTURE WORK

Further testing, characterization and redesign is necessary prior to using this device to research CoG as an indicator of heavy machinery operator fatigue. In specific:

- **Accuracy:** While signal noise is sufficiently low, the error between measured and actual CoG does not achieve the desired accuracy of +/- 2 mm.
- **Robustness to noise:** Testing was satisfactory in a laboratory setting, but the system is not validated under exposure to mechanical and electrical noise.
- **Preload:** A module with a higher force rating and greater preload would allow measurement of tensile forces, increasing the area of CoG measurement.
- **Tilt sensing:** CoG estimation is only valid when the system is parallel to the ground. Error due to tilt can be compensated for by adding an inclinometer.

This work focused on sensor design. Testing in simulators and then in situ, will be needed to confirm first that operator CoG can be accurately monitored and then that we can differentiate between fatigue related CoG shifts and drivers leaning on armrests, operating pedals and conducting other activities. This will require work in developing a test protocol, filtering and algorithms, and finally, evaluating efficacy of the system as a fatigue detection tool.

Further design work will focus on both increasing robustness and decreasing cost, with the aim of a path towards a commercial solution. The Appendix details initial concept work to provide the same 4-point measurement with four strain-gauge equipped flexures, which suggests easier, more compact integration into a seat's mounting.

Lastly, application of our system is not limited to use in heavy machines, but can be extended to CoG sensing on any seat, with applications as diverse as commercial automotive, elderly care to reduce pressure ulcers, and classrooms to study student attentiveness.

REFERENCES

[1] K. Gawali, L. Kirti, V. Aishwarya, S. Aishwarya, and P. Kale, "Driver fatigue detection," International education and research journal, vol. 2, no. 3, 2016.

[2] R. Grace, V. E. Byrne, D. M. Bierman, J. M. Legrand, D. Gricourt, B. K. Davis, J. J. Staszewski, and B. Carnahan, "A drowsy driver detection system for heavy vehicles," in 17th DASC. AIAA/IEEE/SAE. Digital Avionics Systems Conference. Proceedings (Cat. No.98CH36267), vol. 2, Oct 1998, pp. I36/1–I36/8 vol.2.

[3] W.-B. Horng, C.-Y. Chen, Y. Chang, and C.-H. Fan, "Driver fatigue detection based on eye tracking and dynamk, template matching," in *IEEE International Conference on Networking, Sensing and Control, 2004*, vol. 1, March 2004, pp. 7–12.

[4] Y. Nawa, H. Takada, and Y. Matsuura, "A study about the sitting fatigue evaluation of a car driver," the Japan Society of Mechanical Engineers 16th General Meeting of Kanto Branch Proc, vol. 2010.16, pp. 429–430, 2010.

[5] "Air traffic controller fatigue detection method based on clustering analysis, device and system," Jan. 20 2016, cN Patent App. CN201,510,641,780. [Online]. Available: https://www.google.com/patents/CN105261152A?cl=en

[6] R. G. Elbers, M. B. Rietberg, E. E. H. van Wegen, J. Verhoef, S. F. Kramer, C. B. Terwee, and G. Kwakkel, "Self-report fatigue questionnaires in multiple sclerosis, parkinsons disease and stroke: a systematic review of measurement properties," in Quality of Life Research, 2011.

[7] S. Furugori, N. Yoshizawa, C. Iname, and Y. Miura, "Estimation of driver fatigue by pressure distribution on seat in long term driving," vol. 26, pp. 053–058, 01 2005.

[8] H. Nagasaku, K. Yadokoro, T. Inagaki, H. Furukawa, and M. Itoh, "Real-time detection of drivers inattentiveness via body movement analysis," Human Interface Symposium 2005, 2005. [Online]. Available: http://ci.nii.ac.jp/naid/10018899378/en/

[9] J. M. Leach, M. Mancini, R. J. Peterka, T. L. Hayes, and F. B. Horak, "Validating and calibrating the nintendo wii balance board to derive reliable center of pressure measures," Sensorsl, vol. 14, no. 10, 2014.

APPENDIX

Shown in Figure 9, this concept design consists of a flat sheet, cut in a rectangle, with a flexural beam projecting inwards on each corner diagonal. Each of the four flexures is equipped with a strain gages from which the CoG can be calculated as with the preceding design. In practice, the bottom of the sheet would be connected to the seat frame and the tip of each beam to the seat. This design can be fabricated out of sheet metal, with a low part count and is preferable for mass production. Additional, it suggests other flexure-based designs integrated into the seat structure.

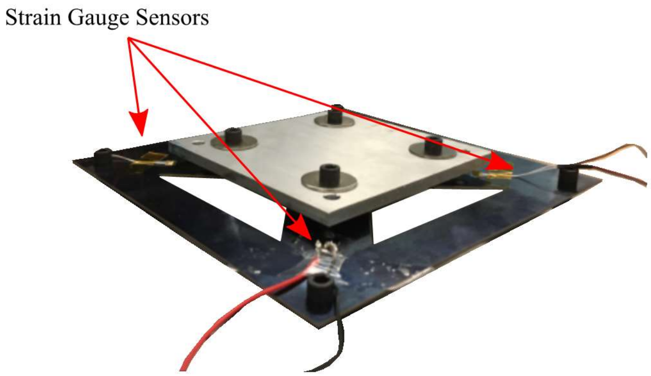


Figure 9: Prototype of 4 beam structure.