Multi-sensor data fusion for precise measurement of a tractor implement performance in the field

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A multi-sensor-based instrumentation system was assessed under static and dynamic conditions to precisely measure a tractor-implement performance in the field. The system was evaluated using a tractor and three different implements, viz. 11-tyne cultivator, three-bottom ridger and nine-row spatially modified no-till drill. The final results were compared with conventional measurement techniques. The range of disparity for wheel slip, draft, inclination angle, fuel consumption, radiator fan speed and forward speed was 4.24–5.99%, 2.63–4.95%, 2.68–7.20%, 3.78–5.64%, 3.37–4.81% and 3.04–4.97% respectively. The system could measure real-time variations in the field and proved to be an energy- and time-saving device.

Keywords: Data logger, instrumentation system, performance assessment, sensors, tractor implements.

AGRICULTURE plays an important role in the Indian economy, providing employment to 60% of the population. The share of agriculture in GDP had increased to 19.9% in 2020–21 from 17.8% in 2019–20. It was the only sector with a positive growth of 3.4% in 2020–21, while all other sectors had a negative growth[1]. The mechanization of agriculture during the 20th century led to major changes in decisions regarding planting, irrigation and harvesting crops[2]. For several years researchers have been experimenting with precision techniques for optimizing the profitability and sustainability of farmers through proper management of farm machinery[3]. Still, there are no proper data that can be used by the farmers to select tractors and implements corresponding to their field conditions for maximum efficiency. Also, such data are required by agricultural implements manufacturers to improve their future designs. Some data have been published in the Regional Network for Agricultural Machinery (RNAM), American Society of Agricultural and Biological Engineers (ASABE), International Organization for Standardization (ISO), Equipment Manufacturers Institute (EMI) Standards, etc., but these are not extendable to other field conditions as they are categorized based on specific geographical conditions or local soil type. Hence, more researchers are inclined towards development of systems for dynamic measurement of tractor-implement performance in the field.

The main parameters of tractor-implement performance include fuel consumption, forward speed, engine speed, power take-off (PTO) torque, PTO speed, three-point linkage force, draft, drawbar pull, engine temperature, wheel slip and implement depth. Earlier research in this field was conducted with the help of mechanical sensors and manual recording of data, which was difficult. Now, with the help of technology intervention in agriculture, digital sensors and instrumentation systems have paved the way for compact systems to be installed on tractors.

A review of published work has confirmed that a large number of researchers have worked in this field (Table 1). Most of the work published focused on measuring one or two performance parameters at a time, and only a few researchers worked on multi-parameter measurements. Recently, several systems have been developed for measuring real-time variations of these parameters in the field[4–9]. Some shortcomings of the developed systems for measuring tractor performance in field from the reviewed work are as follows:

- The developed systems require a lot of space on the tractor for installation.
- Some systems are tractor-specific and not flexible.
- Some systems require a person other than the tractor operator to record data.
- Some systems cannot record dynamic variations of performance parameters in the field.
- A comparative evaluation with respect to conventional methods of measurement is lacking.

Table 1. Review of work in the field

Tractor implement performance parameters	Cited literature
Fuel consumption	11, 12
Drawbar pull	13–26
Forward speed	27–31
Wheel slip	32–36
Tillage depth	37
Draft and forward speed	38
Tillage depth and wheel slip	39
Draft and wheel slip	40

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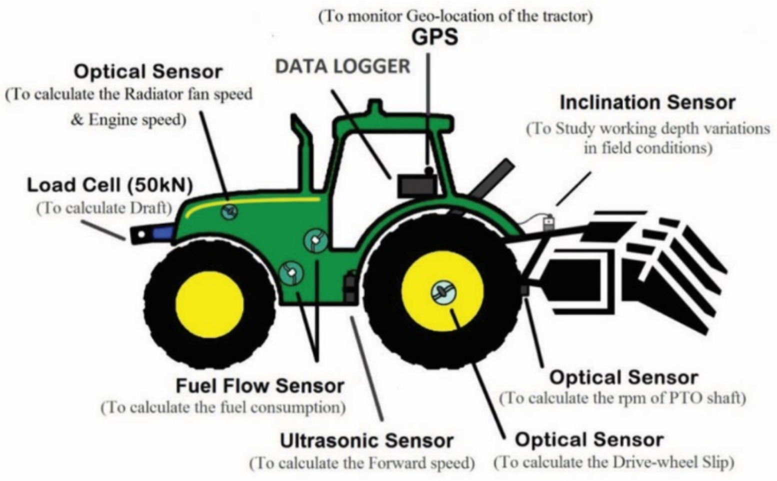

Figure 1. Arrangement of data logger and sensors on the tractor implement system.

Table 2. Technical specifications of sensors used in the instrumentation system

Instrument/sensor (model)	Specifications	Country of origin	Use
Data logger (DataTaker DT85)	128 (approx. 10,000,000 data points), 48 analog (±50 V) sensor inputs, external voltage range: 10–30 V DC, peak power: 12 W (12 V DC 1A).	Japan	Recording and storage of data
Optical sensor (Optex C2DM-11P)	20 m sensing distance, red LED, 10–30 V (DC), emitter: 20 mA, receiver: 15 mA, 10% hysteresis, vibration resistance: 10–55 Hz double amplitude 1.5 mm 2 h in each of the *X*, *Y* and *Z* directions	USA	To calculate slip of left and right wheel To measure engine and radiator fan speed To measure PTO speed
Ultrasonic sensor (Delta DRS1000)	62.1 pulses/km/h, speed range up to 0.8–480 km/h, unadjusted error ±0.34%, 2.4 W power supply	Germany	Forward speed measurement
Load cell sensor (Syskon SI-486U)	50 kN, 10 V (DC), 28°C ambient temperature, safe overload of 120% of rated capacity	India	Draft force measurement
Fuel flow sensor (Burkert Type-8031)	8–36 V DC, 10–100 l/h (2.6–27 gph) measuring range, initialize after ≤0.5 s, 10 bar at 20°C fluid pressure, ±2% accuracy, 0–300 Hz	Switzerland	Measurement of fuel consumption
GPS sensor (Garmin MS-192 GPS 18x)	4.4–5.5 V, 55 mA @ 5.0 V, –185 dBW/min sensitivity, reacquisition takes less than 2s	China	To monitor geo-location and positioning of the tractor
Inclination sensor (Baumer GIM 500R)	Resolution of 0.025°, typical ±0.1% accuracy, ±10°, ±30°, ±45°, ±60°, ±90° sensing range	Switzerland	To study angular variations of working depth of the implement

To overcome these shortcomings, a multi-sensor-based instrumentation system was developed[9]. In the present study, the developed system has been evaluated in the field with three different combinations of tractor and implement: an 11-tyne cultivator, a three-bottom ridger, and nine-row spatially modified no-till drill, and the final results compared with ground-based measurements.

Multi-sensor instrumentation system

A sensor-based instrumentation system was installed on a 28.35 kW tractor (John Deere 5038), without modifying it, for measuring various tractor performance parameters such as drive-wheel slip, draft, fuel consumption, radiator fan speed, engine speed, forward speed, geo-location and angular inclination. It comprised a data logger unit (DT 85) and six different transducers (four optical sensors, two fuel-flow sensors, one universal-type load cell sensor, one ultrasonic sensor, one GPS sensor and one inclination sensor). These analog and digital sensors were connected to the data logger using insulated cables. The sensors were calibrated and the data logger was programed to convert these voltage signals into equivalent tractor implement performance parameters. The tractor battery was used to power the data logger, which powered the sensors in parallel. The sensors, cables and data logger were sealed in several casings to protect them from dust and other environmental parameters in the field. The sensors used in the system were selected based on their availability, sampling frequency, minimum resolution and range. Figure 1 and Table 2 show the sensors' arrangement and technical specifications respectively.

Transducers

- The horizontal traction force of the implement was measured with the help of a load cell (0–50 kN). It was mounted in front of the tractor, and with the help of an auxiliary tractor, the variations of draft force were recorded in terms of voltage fluctuations.
- Two fuel sensors mounted on the inlet and outlet fuel line of the tractor were used to measure fuel consumption. The sensor produced a flow-proportional frequency signal (10,200 pulses/l) which was calibrated to give the fuel flow (l/min).
- The PTO revolution per minute (rpm) was measured using an optical sensor with a response time of 0.5 ms installed above the PTO shaft for counting rotations per minute. The sensor produced PWM (pulse width modulation) signals co-related with the PTO speed.
- To measure forward speed, an ultrasonic sensor with a calibration constant of 0.01610306 km/h/pulse was installed near the left side fender of the tractor at an angle of 45°.
- An optical sensor, similar to the one used for PTO rpm measurement, was installed near the radiator fan to measure radiator fan speed for indirect calculation of engine speed. The engine speed was indirectly calculated from this speed by multiplying it by the ratio of pulleys (1: 1.414) connected to the engine fan and radiator fan.
- A GPS sensor (Garmin MS-192 GPS 18x) was installed over the tractor fender to compute its geo-location.
- For inclination angle, a MEMS (micro electromechanical system)-based sensor was installed on the top link of the tractor. The sensor measured the angular inclinations in terms of current variations, which were calibrated using the data sheet (calibration constant: 0.056 mA/deg).

Performance assessment

Field trials of the developed instrumentation system were conducted at research farms of the Department of Farm Machinery and Power Engineering, Punjab Agricultural University, Ludhiana, India. The initial field trials were conducted on an unploughed rectangular plot (30 m × 45 m) with flat topography and soil type sandy loam with sand, silt and clay proportions of 69.4%, 14.9% and 15.7% respectively, whereas comprehensive field trials, after recalibration of the sensors, were conducted in the fields having similar soil type classification as a sandy loam (Figure 2). The soil parameters were measured at five random locations prior to the tests. The moisture content (dry basis) of the soil was 12.8–14.2%. The average cone index of the soil, measured using a cone penetrometer having a cone apex angle of 30°, was 1.875 MPa. The tractor-mounted (three-point hitch) type implements, viz. an 11-tyne cultivator, three-bottom ridger and nine-row spatially modified no-till drill, were used for the field tests. Before entering the main test plot, a three-point linkage height lever was activated to lower the implement corresponding to plowing depth range of 10–14 cm for cultivator, 16–20 cm for ridger and 8–12 cm for no-till drill, while operating the tractor at an average forward speed of 3.2, 3.9 and 3.2 km/h for cultivator, ridger and no-till drill respectively. The tractor was operated at a suitable gear to maintain the forward speed and depth of operation of the implement. To reduce random errors, three replications were repeated for each measurement.

Figure 2. Photographs showing field trials of the developed instrumentation system.

The accuracy of the developed instrumentation system was measured by comparing the sensor-based values of each performance parameter with ground-based measurements.

- Conventional top-up method was used to validate the readings from fuel-flow sensors[10]. The fuel tank of the tractor was filled to its maximum capacity before initializing the field operation. Then the tractor with the implement attached was made to work in the same field for half an hour, and fuel consumed during the process was recorded and compared with the sensor values.
- A digital tachometer (Metrix TM-4005) was used to measure PTO speed and radiator fan speed for validating the sensor values.
- To measure forward speed, two points were marked with flags on the field as *A* and *B*. The distance between these two points was measured using a measuring tape. Then the tractor attached to the implement was driven at the same gear from point *A* to *B*, and the total time taken during the journey was recorded. The average forward speed was calculated using eq. (1) as follows

$$\text{Speed} = \frac{\text{Distance between points } A \text{ and } B}{\text{Time}}. \qquad (1)$$

- To check the accuracy of the geo-positioning system, five different static geographical positions in the field were chosen, and the latitude and longitude values of the sensor were compared with those from the Trimble GeoXT Geoexplorer 2008 series.

Table 3. Results of field trials using the sensor-based instrumentation system

Description	Slip (%)	Draft (kN)	Inclination angle (radian)	Fuel consumption (l/h)	Radiator fan speed (rpm)	Forward speed (km/h)
Treatment I (11-tyne cultivator)						
Mean	6.44	1.17	1.45	6.52	1780	3.05
Minimum	6.06	1.07	1.33	6.12	1740	2.95
Maximum	6.83	1.26	1.48	6.70	1810	3.37
Standard deviation	0.20	0.13	0.12	0.19	46.61	0.16
CV (%)*	3.11	11.11	8.27	2.91	2.61	5.24
Treatment II (three-bottom ridger)						
Mean	12.85	1.26	1.16	6.56	1920	3.85
Minimum	12.26	1.21	1.13	6.30	1980	3.48
Maximum	12.86	1.32	1.18	6.68	1970	3.88
Standard deviation	0.32	0.11	0.14	0.09	47.60	0.11
CV (%)	2.49	8.73	12.06	1.37	2.76	2.86
Treatment III (nine-row spatially modified no-till drill)						
Mean	7.05	1.06	1.26	6.31	1720	3.25
Minimum	6.97	1.00	1.22	6.11	1704	3.02
Maximum	7.50	1.07	1.29	6.73	1750	3.39
Standard deviation	0.17	0.14	0.14	0.18	49.21	0.10
CV (%)	2.41	13.21	11.11	1.58	2.86	3.08

*CV = (Standard deviation/mean) * 100.

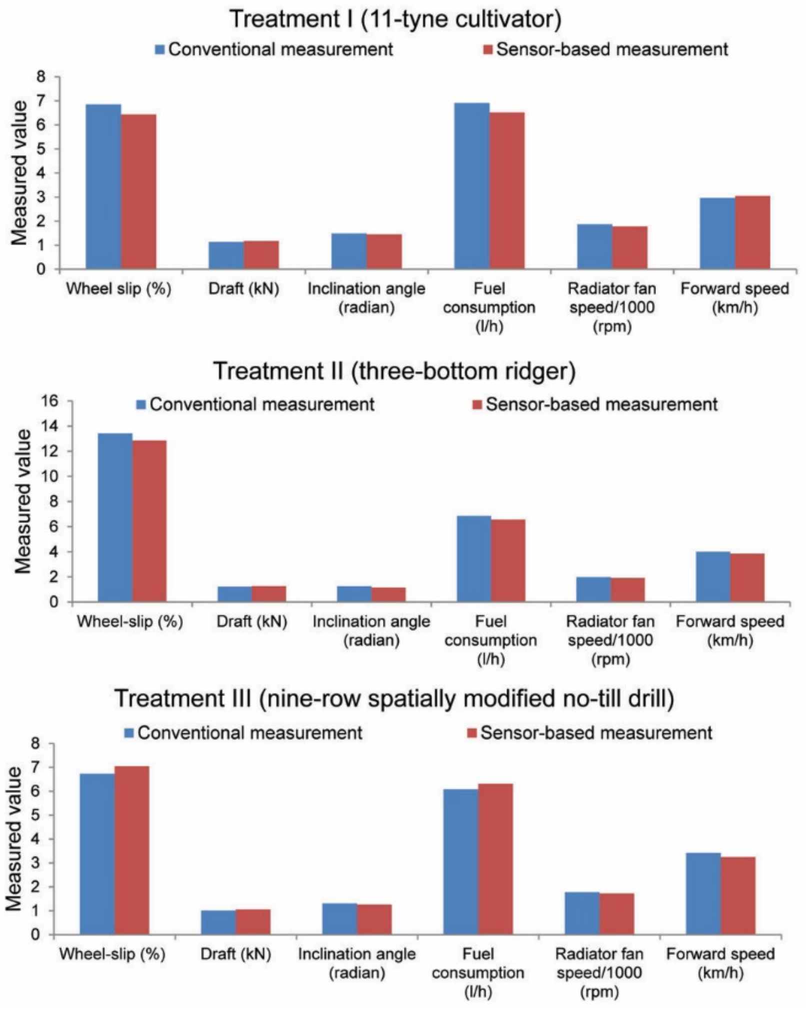

Figure 3. Comparison of tractor implement performance parameters measured using the developed instrumentation system and conventional methods.

Table 4. Variation between mean values of conventional and sensor-based trials

Parameters	Conventional measurement	Sensor-based measurement	Disparity w.r.t. conventional measurement (%)
Treatment I (11-tyne cultivator)			
Wheel slip (%)	6.85	6.44	–5.99
Draft (kN)	1.14	1.17	+2.63
Inclination angle (radian)	1.49	1.45	–2.68
Fuel consumption (l/h)	6.91	6.52	–5.64
Radiator fan speed (rpm)	1870	1780	–4.81
Forward speed (km/h)	2.96	3.05	+3.04
Treatment II (three-bottom ridger)			
Wheel-slip (%)	13.42	12.85	–4.24
Draft (kN)	1.22	1.26	+3.28
Inclination angle (radian)	1.25	1.16	–7.20
Fuel consumption (l/h)	6.85	6.56	–4.23
Radiator fan speed (rpm)	1975	1920	–4.68
Forward speed (km/h)	4.01	3.85	–3.99
Treatment III (nine-row spatially modified no-till drill)			
Wheel slip (%)	6.73	7.05	+4.75
Draft (kN)	1.01	1.06	+4.95
Inclination angle (radian)	1.31	1.26	–3.82
Fuel consumption (l/h)	6.08	6.31	+3.78
Radiator fan speed (rpm)	1780	1720	–3.37
Forward speed (km/h)	3.42	3.25	–4.97

- Gyroscope sensor was used to validate the angular inclinations of the implement with the sensor readings.

Results and discussion

Table 3 presents the mean, minimum, maximum, standard deviation and coefficient of variation (CV) for the measured values of the performance parameters. The draft and slip were recorded highest for the three-bottom ridger followed by the 11-tyne cultivator and nine-row spatially modified no-till drill. This is due to the differences in design and working principle of these three machines. The range of CV for slip (2.41–3.11%), fuel consumption (1.37–2.91%), radiator fan speed (2.61–2.86%), and forward speed (2.86–5.24%) was within the acceptable limits, which showed the degree of consistency and uniformity in the measurements. For other parameters, such as draft (8.73–12.06%) and inclination angle (8.27–12.06%), CV was found to be high. The large range in the draft may be due to field irregularities which mainly depend on the field conditions like soil type, soil structure, compaction level and soil moisture content at different locations in the field. Further, the angle of inclination is dependent on the draft vis-à-vis depth of operation, thereby giving a higher range of CV.

Figure 3 compares tractor implement performance metrics assessed using the developed instrumentation system and traditional methods. Both strategies yielded reasonably similar results. Table 4 shows the disparity between data collected using the sensors and traditional techniques. Depending on the parameter, the disparity for a particular method had both positive and negative values, irrespective of the type of machine used. According to results from the comprehensive trials, the accuracy of the instrumentation system for all performance metrics was above 90%, which is satisfactory. Wheel slip, draft, inclination angle, fuel consumption, radiator fan speed and forward speed showed differences in the range 4.24–5.99%, 2.63–4.95%, 2.68–7.20%, 3.78–5.64%, 3.37–4.81% and 3.04–4.97% respectively, for the three machine types.

Conclusion

The sensor-based data acquisition system, developed without modifying the tractor, was assessed under static and dynamic conditions to measure the main tractor performance parameters, and the data were compared with ground-based measurements. The accuracy with respect to conventional measurement techniques in measuring the average value of performance parameters of the tractor implement in the field was found to be greater than 90%. The multi-sensor-based system is portable, compact, convenient to use, and proves to be an energy- and time-saving device while providing data within acceptable accuracy levels. The system has potential to be fitted on any make and model of 2WD or 4WD tractors for field trails and evaluation of agricultural implements. However, comprehensive field trials under varying soil conditions need to be conducted with more implement combinations before any recommendations to the farmers.

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