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VIBRATIONS LEVELS ASSESSMENT OF A ROBOTIC INTRA-ROW WEEDER USING LOW-COST DATA ACQUISITION SYSTEM

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ABSTRACT. Automated weeding is a way to increase efficiency in the control of invasive plants. Soil characteristics can influence the performance of weeder mechanisms. The objective of this work was to determine the vibrations levels of a robotic intra-row weeder mechanism for different operating conditions and provide information to correlate with soil conditions. The data acquisition system was composed of a single-board computer and a triaxial MEMS accelerometer. The computer was programmed in C++ to acquire vibration measurements. The accelerometer was mounted to the bearing housing of the rotary tine shaft. Vibrations of the weeder mechanism were first measured without soil contact for different angular velocities of the rotary tine disk. Then, vibrations were monitored in different soils (dry and moist loam soil and sand) for three angular velocities of rotary tines (25, 50 and 100 rev/min) and two tine depths (25 and 50 mm). RMS accelerations and the frequency spectrum were used to evaluate the vibrations levels. Moist loam soil and sand had the highest and lowest increases in accelerations, respectively. The analysis showed it is possible to correlate vibrational characteristics with soil conditions that may exist during intra-row weeding. In addition, mechanical vibrations in an intra-row weeder can be monitored using a low-cost and user-friendly system.

Keywords. mechanical vibrations, MEMS accelerometers, mechanical weeding, single board computer, soil conditions.

Introduction

Weed control is one of the most important agricultural practices to obtain high yields of different crops and vegetables. Automation of weeding operations is a way to increase efficiency in the control of invasive plants and to reduce costs, by reducing labor and pesticide usage. Robotic weeders can determine and differentiate weed plants from crop plants, and at the same time, remove weed plants with precisely controlled devices (Bakker, 2009). While available inter-row weeding technology performs well, intra-row weed control is more challenging (Jiken, 2016).

Different weeder types are available. According Mouazen et al. (2007) the selection of an effective mechanical weed control system depends on two main sets of factors. First, the uncontrollable factors which involve weather and soil properties, while the second group are the controllable factors, such as tine and implement design and machine settings. The soil texture and soil physical conditions have to be taken into consideration in the adjustment of machines to optimize weed control efficacy with minimal crop damage. Weeders that work in sandy soils may also perform well in clay soils at optimum soil moisture contents, but perform poorly at other moisture contents. This variability in weeder performance may lead to requirements of different weeders for clay soils at high and low moisture contents. Stones are another complicating factor for mechanical weeding, leading to damage or reduced effectiveness of some weeders, while others may be mostly unaffected (Merfield, 2016).

Soil type, operating conditions, and their interactions can influence the behavior and dynamics of weeding mechanisms. Weeder mechanism dynamics can be monitored through vibration signals measured at specific points on the machine. Vibration analysis can detect unbalanced and misaligned components, loose parts and assembly errors. Furthermore, it can provide information for validating mathematical models and optimizing mechanical designs. When vibration monitoring is done continuously in real-time operation, it may be possible to identify changes in the soil conditions in which the weeder is operating. With this information, optimal weeder adjustments can be made in real time.

Sensors for agricultural equipment must be low cost and robust. Micro-Electro Mechanical Systems (MEMS) technology has gained widespread acceptance in several industrial segments including automotive, industrial, medical and even military applications. Pressure sensors, accelerometers, optical devices and microfluidic devices dominate the MEMS market typically. The advantages of MEMS-based sensor technology for monitoring mechanism dynamics include low cost, low weight, small size, and very low power consumption (Younis, 2011; Hartzell et al., 2010).

MEMS accelerometers have been used in different applications of mechanical vibrations analysis. Aiello et al. (2012) used MEMS accelerometer to measure hand-arm vibrations in harvesting processes using hand-held shaker tools. They demonstrated that technologies such as MEMS accelerometers and wireless networking allow a revolutionary approach to safety management, by promoting the development of low-cost devices for real vibration monitoring.

The MEMS accelerometer can be used with low-cost, single-board computers (e.g. Arduino, Raspberry Pi or Beaglebone) to monitor vibrations. The main characteristics of these single-board computers are their low-cost, high portability and configurability (Travaglione et al., 2014). Abreu et al. (2013) used Beaglebone and Raspberry Pi to develop autonomous vibro-acoustic monitoring system for different purposes like ambient noise and vibration monitoring in civil construction, highlighting an open source philosophy.

The hypothesis that precedes this work is that it is possible to use a low cost and robust system for mechanical vibrations determination in different agricultural and industrial machinery. In this way, this paper proposes the use of a single-board computer coupled with MEMS accelerometers to determine the vibration levels of an automatic weeder and investigate their correlation with soil conditions.

Methodology

The mechanical vibrations tests were conducted in the Off-Road Machine System Laboratory, at Iowa State University (ISU), Ames, Iowa. An automatic intra-row weeder was used for the test, which has a circular disk that rotates about a vertical axis, with four tines mounted on it. This tine mechanism is attached to a pivoting arm that was designed to move the rotary tine between crop plants in the row (Figure 1). The weeder units are attached in a tool bar which is mounted to a tractor’s three-point hitch. Electrical smart motors (SM34165DT and SM3416DT, Moog Animatics, Mountain View, CA) were used for controlling the rotary tines angular velocity and pivoting arm movement. The pivoting arm was programmed to work at specific frequencies, which were dependent on the tractor-weeder forward speed.

(a) (b)

Figure 1. Automatic weeder used in vibrations tests mounted in a tractor (a) and the weeder mechanism with details of its components (b).

The vibration measurement acquisition system consisted a BeagleBone Green Wireless (BBGW, Beaglebone.org, Figure 2) board and a triaxial MEMS accelerometer (ADXL345, Analog Devices, Cambridge, Massachusetts, USA; Figure 2). Communication between these two devices was established using a standard I^2C interface. The accelerometer provides digital output with good precision, a gravity range selectable up to 16g, ready to use functions such free-fall detection and low power consumption. The ADXL345 is well suited for mobile device applications, measuring static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration resulting from motion or shock (Analog Devices, 2017). The BBGW is a low-cost single board computer with different applications in sensor development and variable measurements, high processor capacity and open-source Linux.

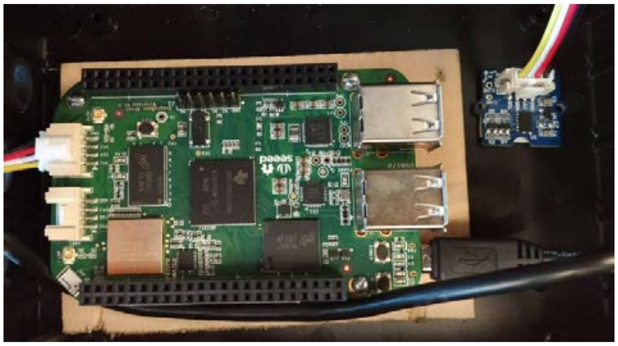


Figure 2. Single board computer Beaglebone Green Wireless® and the ADXL345 digital MEMS accelerometer used on vibrations tests.

A program using a Linux terminal was developed to collect vibration data, which was based on C++ code adapted from Molloy (2012). The vibration measurements were saved in internal memory and were transferred to a PC after the acquisition period. Vibration levels were characterized by RMS accelerations and frequency spectrum. The former characterizing the magnitude of the vibrations, and the latter containing the spectral signature of the vibrations.

The vibration signals were sampled to 150 Hz to avoid aliasing, according the Nyquist theorem (National Instruments, 2016), based on frequencies of pivoting arm and the rotary tine mechanism angular velocity. The high frequency of rotary tines used on vibrations tests was 1.7 Hz, equivalent to angular velocity of 100 rev/min. The sampling rate was much higher than the operating frequency for the rotary tine mechanism. The accelerometer was mounted on a bearing housing which supported the rotating tine mechanism. Each vibration measurement had a duration of 15 seconds.

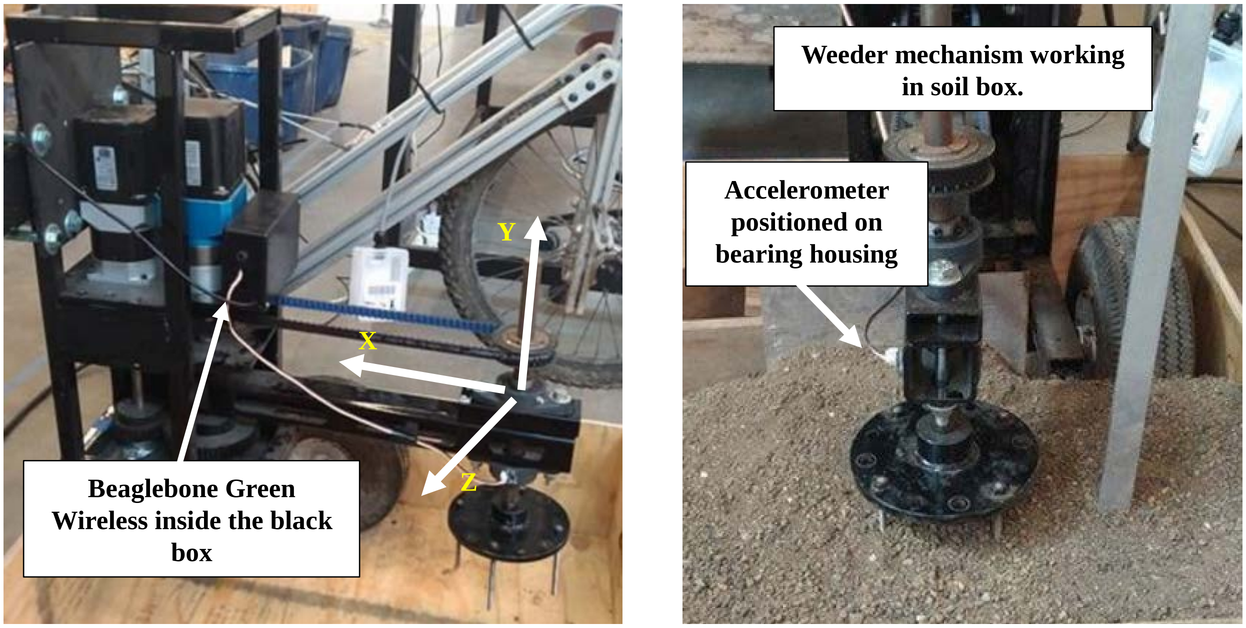
The first test investigated the vibrations levels on the intra-row weeder mechanism as a function of the rotary tines angular velocity. The velocity was varied to three levels, 25, 50 and 100 rev/min, without soil contact. Measurement of vibrations under these conditions made it possible to determine the RMS vibrations without interference from the soil. These angular velocity levels were same utilized by Jiken (2016). The second set of experiments aimed to investigate the effect of tine depth (25 and 50 mm) on vibrations levels. It was realized three replications for each combination between tine depth and rotary tines angular velocity. The tines are made of steel and are cylindrical with a diameter of 6 mm. For this test, vibration measurements were acquired only with the rotating rotary tines without arm movement to identify the influence.

A plywood box with dimensions of the 0.76 m x 0.76 m x 0.20 m was built and was filled with soil up to 0.15 m. The weeder mechanism was located over the soil. Before each new test, the soil was repositioned and compacted slightly. Three soil conditions were analyzed: dry loam, moist loam and sand. The moist loam was kept close to a friable state, a condition suitable for agricultural operations, such as weeding. The moisture content of the soils was determined (Table 1). Figure 3 shows the accelerometer positioned on the bearing of weeder mechanism and soil box built to laboratory tests, with reference measurement axis of the sensor.

Table 1. Main characteristics of soil used in vibrations tests on intra-row weeder mechanism.

Soil condition	Textural class	% Sand	% Silt	% Clay	Moisture content (%)*
Dry	Loam	48.38	26.11	16.80	3.00
Moist	Loam	48.38	26.11	16.80	16.58
Dry	Sand	100	0	0	-

* Determined on a dry basis



(a) (b)

Figure 3. Weeder mechanism used to vibrations analysis: (a) Beaglebone positioning and reference measurement axes and (b) accelerometer positioned on the bearing housing and soil box built for laboratory tests.

The mechanical vibrations were characterized by RMS accelerations along x, y and z axes. As shown in Figure 2(a), the x axis is along the length of the pivoting arm, the y axis is along the axial direction to the angular velocity axis of the rotary tines, and the z axis is in the transversal direction of the pivoting arm. The mechanical vibrations of the weeder mechanism without soil were used as a baseline, in terms of acceleration levels. Subsequently, for three soil conditions, the average RMS vibration levels for each axis were calculated for each rotary tines angular velocity associated with each tine depth. The differences among the RMS acceleration values were calculated for each soil condition comparing with the baseline. This helped identify which angular velocity and tine depth had the greatest influence to detect differences in the soil conditions. This verifies it is possible to develop a mechanical vibrations monitoring system capable of characterizing soil conditions in agricultural field operations.

Results and Discussion

RMS vibration levels for the weeder mechanism

The results presented are only a part of the analysis to determine the vibration levels of an intra-row weeder mechanism and the influence of soil characteristics on them. In this part, the measured RMS vibration levels were compared as the weeder mechanism rotated at three different angular velocities (25, 50 and 100 rev/min), first without contact with soil and subsequently, in three soil conditions (dry loam, moist loam and sand) and two tine depths (25 and 50 mm). The RMS vibrations levels are presented as measured along x, y and z axes (Tables 2, 3 and 4).

Without soil, the highest value was observed along the y axis at an angular velocity of 100 rev/min and was 0.184m s^{-2}. In the y axis, increases vibrations occurred with increases of the angular velocity. This phenomenon was not observed for the x and z axes. For the velocity of 50 rev/min, along the x axis, the vibrations were observed to be a lower value (0.056 m s^{-2}) and along the z axis, a higher value (0.094 m s^{-2}). These values were used as references for comparison with acceleration values when the mechanism was operating in contact with different soil conditions.

Table 2. RMS vibration (m s^{-2}) for weeder mechanism working in three soil condition, three rotary tine angular velocities (25, 50 and 100 rpm), two tines depth (25 and 50 mm) along the X axis.

Angular velocity (rpm)	Without soil	Dry loam		Moist loam		Sand	
		D=25 mm	D=50 mm	D=25 mm	D=50 mm	D=25 mm	D=50 mm
25	0.061	0.0567	0.0628	0.0580	0.0620	0.0558	0.0565
50	0.056	0.0791	0.0778	0.1094	0.1185	0.0760	0.0870
100	0.066	0.0957	0.1085	0.1722	0.2140	0.0793	0.0773

*D – Tine Depth

Table 3. RMS acceleration (m s^{-2}) for weeder mechanism working in three soil condition, three rotary tine angular velocities (25, 50 and 100 rpm), two tines depth (25 and 50 mm) along the Y axis.

Angular velocity (rpm)	Without soil	Dry loam		Moist loam		Sand	
		D=25 mm	D=50 mm	D=25 mm	D=50 mm	D=25 mm	D=50 mm
25	0.111	0.0821	0.1053	0.0912	0.1195	0.0769	0.0768
50	0.143	0.1675	0.2185	0.3373	0.5561	0.2286	0.3083
100	0.184	0.1901	0.2838	0.4312	0.5364	0.1892	0.1597

*D – Tine Depth

Table 4. RMS acceleration (m s^{-2}) for weeder mechanism working in three soil condition, three rotary tine angular velocities (25, 50 and 100 rpm), two tines depth (25 and 50 mm) along the Z axis.

Angular velocity (rpm)	Without soil	Dry loam		Moist loam		Sand	
		D=25 mm	D=50 mm	D=25 mm	D=50 mm	D=25 mm	D=50 mm
25	0.078	0.1217	0.1729	0.2676	0.3335	0.0877	0.0957
50	0.094	0.1675	0.2417	0.5289	0.5925	0.1007	0.1240
100	0.088	0.1598	0.2782	0.9485	1.2402	0.0991	0.1638

*D – Tine Depth

For the same angular velocity, there was an increase in vibrations when working at a higher tine depth. Exceptions were observed for dry loam working at 50 rpm, along the x axis, and for sand along the x and y axes, at 100 rpm. Generally, for the same tine depth, vibrations increase with increases in angular velocity. An exception to this trend was observed in sand, along the x axis (50 mm), the y axis (25 and 50 mm) and the z axis (25 and 50 mm). Higher values were observed at 50 rpm. The same occurred for moist loam (50 mm) along the y axis and (25 mm) for the z axis. This observation indicates the system may be more sensitive to differences in soil conditions at higher angular velocities.

Table 5. Percent increase in RMS vibrations in the weeder mechanism for each soil condition worked for those observed without soil contact, for three rotary tine angular velocities and along X, Y and Z-axes, using the average values between two tine depths.

Velocity (rev/min)	Dry loam			Moist loam			Sand		
	X	Y	Z	X	Y	Z	X	Y	Z
25	-1	24	89	-1	-5	285	-7	-31	1
50	39	153	119	103	212	499	45	88	20
100	55	166	149	193	162	1146	19	-5	50

Among the three soil conditions, the lowest increase in vibrations was observed for sandy soil (sand). It is also noted that for the lower angular velocity (25 rpm), for the x and y directions there was a decrease in observed accelerations. The greatest increase in vibrations observed for sand was 88%, along the y axis, associated with an angular velocity of 50 rpm. Moist loam soil had the largest increase in vibrations, especially in the z direction. When the mechanism was rotated at an angular velocity of 100 rpm, the vibration magnitude increased by 1,146 %. Although there was an increase in the vibrations in dry loam, this increase was small when compared to moist loam, mainly along the z axis.

For moist loam soil, the moisture content changed the soil consistency. Soil consistency is the strength with which soil materials are held together or the resistance of soils to deformation and rupture. Moisture content can influence in resistance of the soil to deform or rupture (FAO, 2017). Changes on soil consistency may increase the accelerations observed when compared to the same drier soil. The presence of more soil aggregates was observed in the moist loam soil compared to the dry soil. Thus, greater force may be required to break down the soil aggregates and consequently higher accelerations can be observed. Another factor to consider is that at higher moisture content in soil, there is greater possibility of soil adhesion in the tines, causing unbalance of the rotary tine and increasing the accelerations. Loam soil has a higher soil cohesion than sandy soil (Geotechdata, 2017). Comparing dry and moist loam soils with sand, the higher acceleration values may be associated with the soil cohesion, which may have caused the increase of the vibrations.

Considering the vibration levels, for the different soil conditions used in this test, a great difference can be observed in the RMS vibration amplitudes. Mechanical vibrations data like RMS acceleration along with frequency spectral information all have potential to identify differences in soil conditions.

Conclusions

Mechanical vibrations can be monitored in the intra-row weeder using a low-cost and user-friendly system. Furthermore, even though it is in the early stage of studies, it appears promising, by means of monitoring mechanical vibrations, to develop a device capable of identifying soil types and conditions used in different agricultural operations.

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