Design and Evaluation of a Machine Vision System and Mechatronic Drive for a Pneumatic Seed Meter for Corn

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ABSTRACT

A pneumatic seed meter equipped with a machine vision system and a mechatronic drive was developed to reduce the incidence of missed seeding during mechanical corn planting. The machine vision system monitored the seed plate and checked if seeds did not attach to the seed plate holes. The rotation speed to the seed plate was adjusted by the mechatronic drive based on the presence and absence of seeds attached to the seed plate holes. The reliability of the mechatronic drive in regulating the seeding rate, and the accuracy of the machine vision system in identifying filled and unfilled seed plate holes were both tested. The combined system of the machine vision system and the mechatronic drive was also tested if it can effectively reduce the incidence of missed seeding in a stationary laboratory rig under simulated speed settings of 2kph, 4kph, and 6kph. It was found out that the drive did not maintain a consistent seed delivery rate, which can be attributed to the limited processing capacity of the microcontroller used to control the drive. The machine vision system was highly accurate as it only committed a 0.2564 % error out of 780 images. The machine vision system of the seed meter, at 2kph and 4kph simulated speed settings, committed significantly, at 95% level of confidence, less missed seeding in the conducted treatments in comparison to the setup where the seed meter was operated without the machine vision system. The treatments wherein the machine vision system was used, however, committed more missed seeding at 6kph simulated speed setting.

Keywords: precision planter; image processing; mechatronic drive system; microprocessor; microcontroller; OpenCV

INTRODUCTION

Precision planters are crop establishment equipment that precisely control the seed delivery to maximize the potential of planting materials. A planter has a seed meter (SM), furrow opener, furrow closer, seed tube, and ground wheel. The SM houses a vertical seed plate (SP) with holes arranged radially. The holes act as ports where air flows due to the negative pressure in the vacuum chamber. This mechanism catches seeds from a seed sump and holds them as the SP rotates and transfers the seeds to the seed tube.

Li, *et al.* (2016) reported in their paper several technologies and emerging trends on precision planters along with new planter models. Numerous designs of precision planters have been released in the market – ranging from small machines that target small and hilly farmlands to large planters for wide plains. The diversity of planting machinery designs thrives due to the variation of farmlands where mechanical planters are used. Appropriate technology that suits the terrain and size of farmland is a major consideration in the use of a certain machinery.

In the case of Philippines where landholdings and parcels are small with uneven terrain slopes, large precision planters are not applicable. Small tractors attached with four to six row planter implements would be much more appropriate for most farmlands in the country. Compared to large precision planters, these smaller variants perform less efficient as described by Li, *et al.* (2016). The problem of missed seeding remains an issue for operators of these small planters.

Majority of corn farmers in the Philippines use manual and animal drawn tools in planting corn. Pneumatic planters with four to six row seeders are utilized only by progressive farmers with enough financial capabilities and farmer groups with financial support from the government. Orozco (2011) explains that the patronage on these planters is limited by the high acquisition cost and difficulty in maintenance due to lack of available spare parts. This is because the market of pneumatic planters is saturated by imported units wherein tariffs, taxes and import costs augment the cost of these machines. Moreover, spare parts are not readily available in the country. Since these machines were developed in other countries where terrain and cultivation practices are different, these machines do not fit with the needs of common farms.

A local design of pneumatic corn seeder has been developed by Orozco (2011). The machine was designed to fit with the local farming practices and utilized local materials using local manufacturing methods. This ensures that the machine matches the requirements of local farmers and at the same time enables local manufacturers to fabricate and repair the machine. Tests on the machine's performance reveal that on actual planting operation, the spacing between the hills deviate 13 to 16 cm from the average hill spacing of 23cm. The variability of hill spacing, as identified by the author, can be attributed to the failure of the machine to fill all the SP holes. This causes missing hills (MH) in the row. The lack of a hill between two hills means that the distance between the two hills is twice than the expected hill spacing. Another probable cause of variability in seed spacing is the slippage of the ground wheel during operation. Slippage causes failure of the metering device to release a seed on the expected moment thus increasing the expected hill spacing.

The incidence of MH or large gaps between hills requires another manual planting operation to fill the MH, however, it would increase the cost of planting at it requires additional labor. This problem can be avoided by inspecting plate during runtime to locate empty holes and avoid MH by advancing the rotation of the SP and set an adjacent hole with seeds at the opening of the seed tube at the right time. One approach to reduce the missed seeding in the design is to directly monitor the SP inside the SM and adjust the planting parameters instantaneously to maintain uniform planting distance and rate. The process can then be automated using a machine vision system (MVS) installed on the SM itself. This approach will have two components that need to be considered. First is the mechatronic drive (MD) and the second is the MVS for SP monitoring.

The use of MDs as alternative to conventional drive systems for SMs have already been explored by several research and manufacturing companies as cited by Li, *et al*. (2016). The paper, however, noted that the use of MDs in planters limits the planting speed. The planting speed is restricted by the size of the motor used, since torque requirement increases as planting speed increases. To compensate the limited torque of motors used in MDs Li, *et al*. (2015) replaced the mechanical drive of a SM by Song, *et al*. (2014). The planter was driven by a stepper motor and gear assembly and was controlled by a microcontroller. The MDs operation was based on the readings taken from a rotary encoder connected to the ground wheel. The use of geared system for the MD increased the complexity of the machine, however. Li, *et al*. (2016) pointed out that most research and development geared towards the MDs use large stepper motors that can deliver high torque at high rpm at the expense of additional weight for the planter.

When it comes to the application of a monitoring system inside the SM, gaps are present. SP monitoring is not commonly practiced for corn planters. Seed detectors, instead, are installed inside in the seed tube. The seed detectors count the seeds passing through the seed tube but doing so would only detect doubles and missed seeding. There would be no chance for adjustment to compensate for detected missed seeding. The MVS would be able to detect possible missed seeding even before seeds are dropped through the seed tube.

This paper is a local study on the application of automated systems to large agricultural machineries. It is envisioned to open the potential of developing a locally suitable precision planter. This will serve as the basic platform that can be modified to incorporate the needed equipment and sensors for performing precision planting. The technology would improve the performance of planting equipment manufactured in the country. The machine is expected to reduce if not eliminate the occurrence of missed seeding during planting. The reduction of missing hills will reduce the needed labor input needed for replanting. As a result, the cost of production will be reduced. The benefits derived from the output of this study is not constrained to the value chain of corn alone. The concept can be easily applied to other agronomic crops such as legumes with minor modifications to the SP and algorithm. Not only the farmers are to benefit from this. If the technology is to be mass produced to meet the demand for a highly reliable planting equipment for local consumption, local manufacturers will have to manufacture and market the machine. This will give local manufacturers the chance to infiltrate the market of pneumatic and precision planters, which is dominated by imported machineries. This study will aid in improving and revolutionizing the local agricultural machinery manufacturing industry. Such will not only have an impact on the agricultural industry but also on the Philippine economy.

The primary objective of the study was to develop a precision SM for a corn planter. Specifically, the study aimed to design and fabricate a precision SM for a pneumatic corn planter fitted with MVS components and MD; to develop an image processing workflow capable of detecting filled and unfilled holes; to develop a workflow for controlling the planter drive; and to evaluate the reliability of the machine vision controlled drive in maintaining the rate of seed delivery. To achieve this, the methodology focused on designing a SM that can be driven using a MD with a stepper motor as prime mover, and on developing software that can detect seeds attached to the SP and regulate the angular speed of the prime mover's shaft. A test was conducted to evaluate if the drive can deliver seeds to the seed tube at uniform intervals. Another test was conducted to assess if the MVS can accurately distinguish filled holes from empty holes in the SP. Lastly, a test was conducted to determine if the incidence of missing hills can be reduced by the MVS and the MD.

METHODOLOGY

This section provides the description of the hardware, software and the tests conducted on the SM. The Materials section contains the discussion on the concept of operation and the hardware used

to construct the SM. The Methods section details the tests conducted to evaluate the performance of the MVS, the MD and the SM.

Materials

The SM had two components, namely, the electro-mechanical component and the control software. The electro-mechanical component consisted of all the hardware needed for the actual metering, controlling the drive axle, and supplying electrical power to the entire system. The control software component consists of the two compiled programs that were run by the single board computer (SBC) and microcontroller. Figure 1 shows the SM installed in the Laboratory test rig.
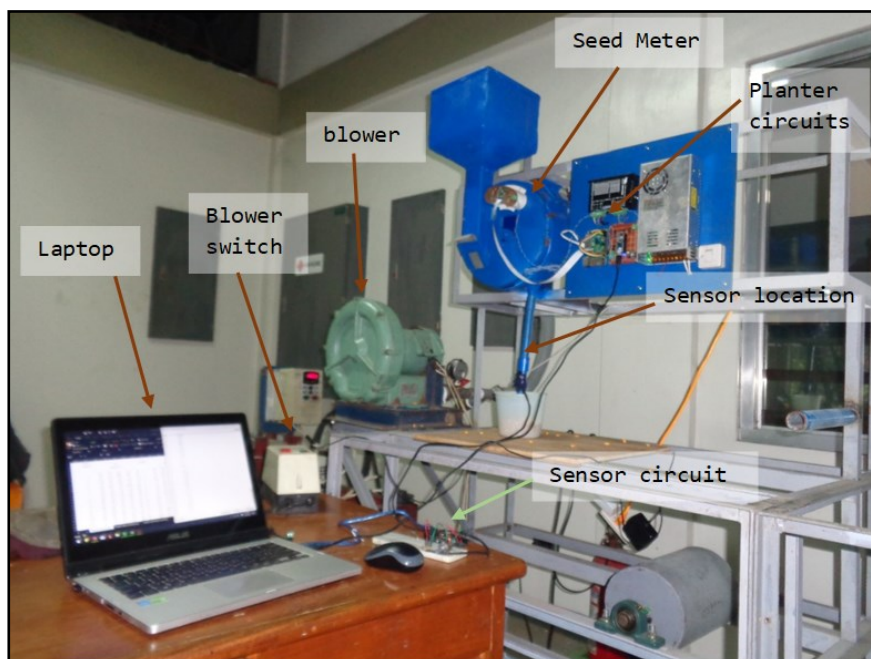
Design of Electro-mechanical Component of the Seed Meter

The design of the planter, shown in Figure 2, is based on the locally fabricated pneumatic corn seeder design of Orozco (2011). The body of the SM is constructed with Acrylonitrile Butadiene Styrene using Fused Filament Fabrication. The SM body has a diameter of 274 mm and a width of 100 mm. It consists of two main components, the seed chamber, and the cover. The cover houses the camera module with light-emitting diodes for illumination, the seed reservoir that contains the seeds for planting, and the seed scraper that guides the metered seeds towards the seed tube. The parts of the seed chamber are the vacuum chamber that enclosed the low-pressure space that enables the attachment of seeds to the SP, and

Figure 1. The developed seed meter mounted in laboratory rest rig showing the major parts and equipment used for the tests conducted
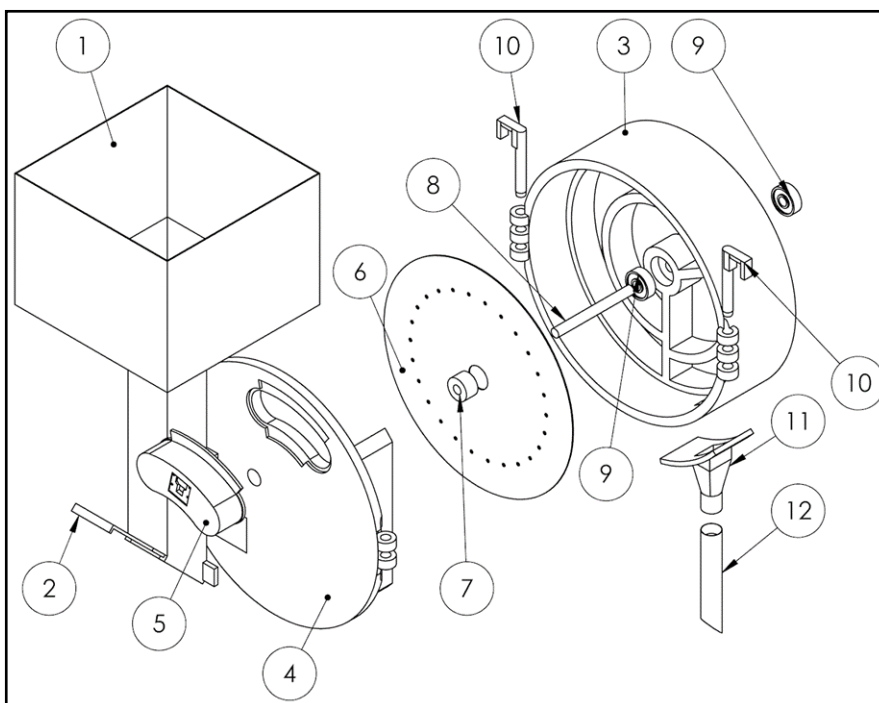

Figure 2. Exploded view of SM showing (1) hopper, (2) hopper drain cover, (3) planter case, (4) planter cover, (5) camera mount, (6) SP, (7) SP bushing, (8) planter axle, (9) bearing, (10) hinge pin, (11) seed tube connector, and (12) seed tube.

the mounting points for Z6000 bearings for the SP assembly.

The vertical SP (Figure 3) is constructed using a 1.2 mm thick stainless-steel sheet, which is cut into a 250 mm diameter disk with the holes following the recommended specifications for corn planter SPs by Önal *et al*. (2010). A 25 mm diameter with 10 mm bore cold rolled steel bushing welded to the SP is used to mount the SP to the shaft and is secured by two 6 mm set screws. The axle is a 10 mm diameter and 100 mm long round bar. This is supported by two Z6000 bearings mounted at the posterior of the SM body. A Wantai 85BYGH450D-002AG5 Nema 32 stepper motor is directly coupled to the axle of the SP.
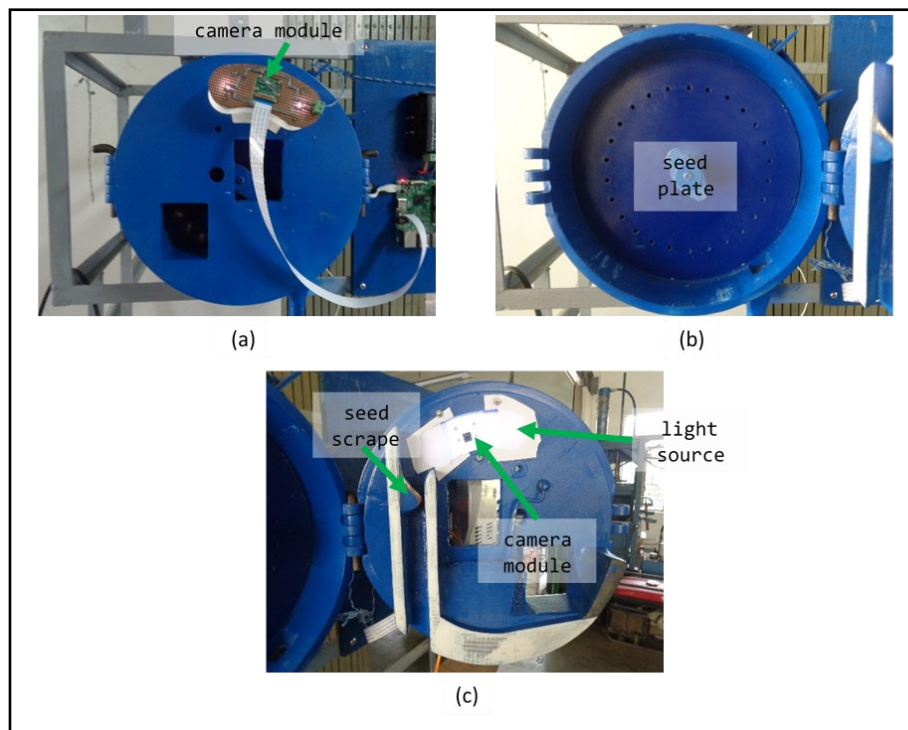
The stepper motor is controlled using a Wantai DQ542MA Microstep driver. The driver is set to operate at 4.2A peak and 3.0A RMS and is configured to supply full current during standstill. The steps-per-revolution is set to 400. An ATmega328 microcontroller is used to produce the pulses that operate the micro-stepping driver and interpret commands from a SBC (Raspberry Pi 3 Model B). The SBC processes the images of the SP, which are taken from a camera module mounted inside the SM. The mechanical and electronics parts of the SM are shown in Figure 2.

Figure 3. Seed meter case showing (a) front of cover, (b) inner chamber with seed plate and (c) back of cover.
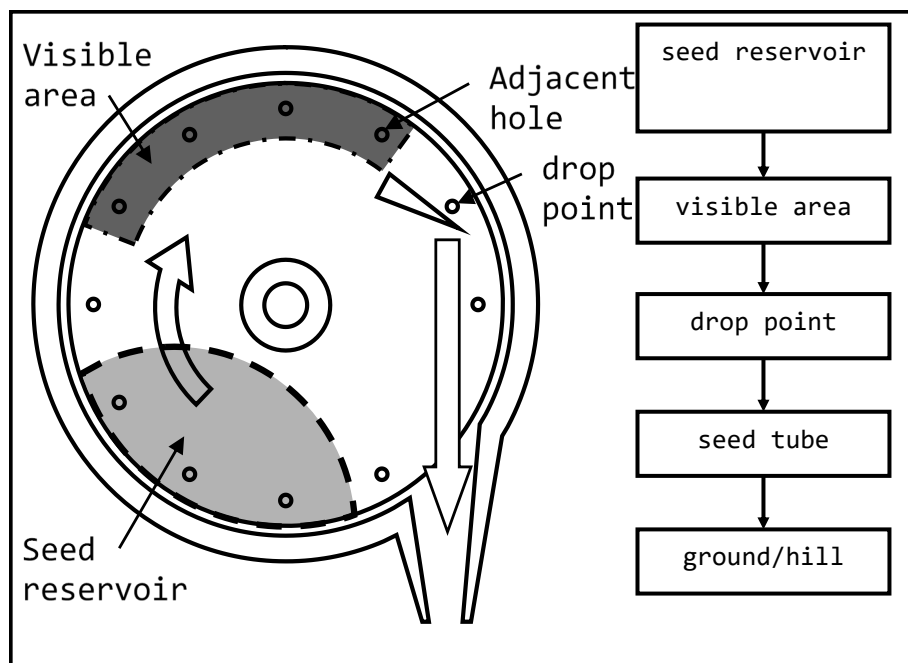

Figure 4. Diagram of the SM describing the direction of seed flow and relative areas covered by seed reservoir, visible area, and drop point as described by Borja *et al*. (2018).

Development of the Control Software

The conceptual design of the software control is described in a paper by Borja *et al.* (2018). The computer program for seed detection and feedback is written in C++ and utilize the OpenCV (version 3.3) library for processing images captured using a Camera Module of Raspberry Pi. Proper timing has to be observed to achieve a near real-time operation of the planter, thus, the choice for the programming language along with a C based library. The program was written with processing speed in consideration to maintain processing latency at a minimum.

There are three regions inside the SM that were considered for the operation of the SM – seed reservoir, visible area, and drop point (Figure 4). Seeds are deposited from the hopper to the seed reservoir of the SM. Individual seeds then attach to the holes of the SP due to air suction thru the holes. Seeds travel upwards as the SP rotates clockwise until they reach the visible area, which is an area in the SP that is within the field of view of the camera module. Beyond the visible area is the drop point, which is where the suction is cut, and the seed is subsequently scraped off from the SP to deliver the seed to the seed tube.

The program checks whether there are unfilled holes within the visible area and makes sure that there will always be a seed next to the drop point. If an unfilled hole is detected in the visible area, the SP rotation is increased to compensate for the gap. This immediately brings a seed next to the
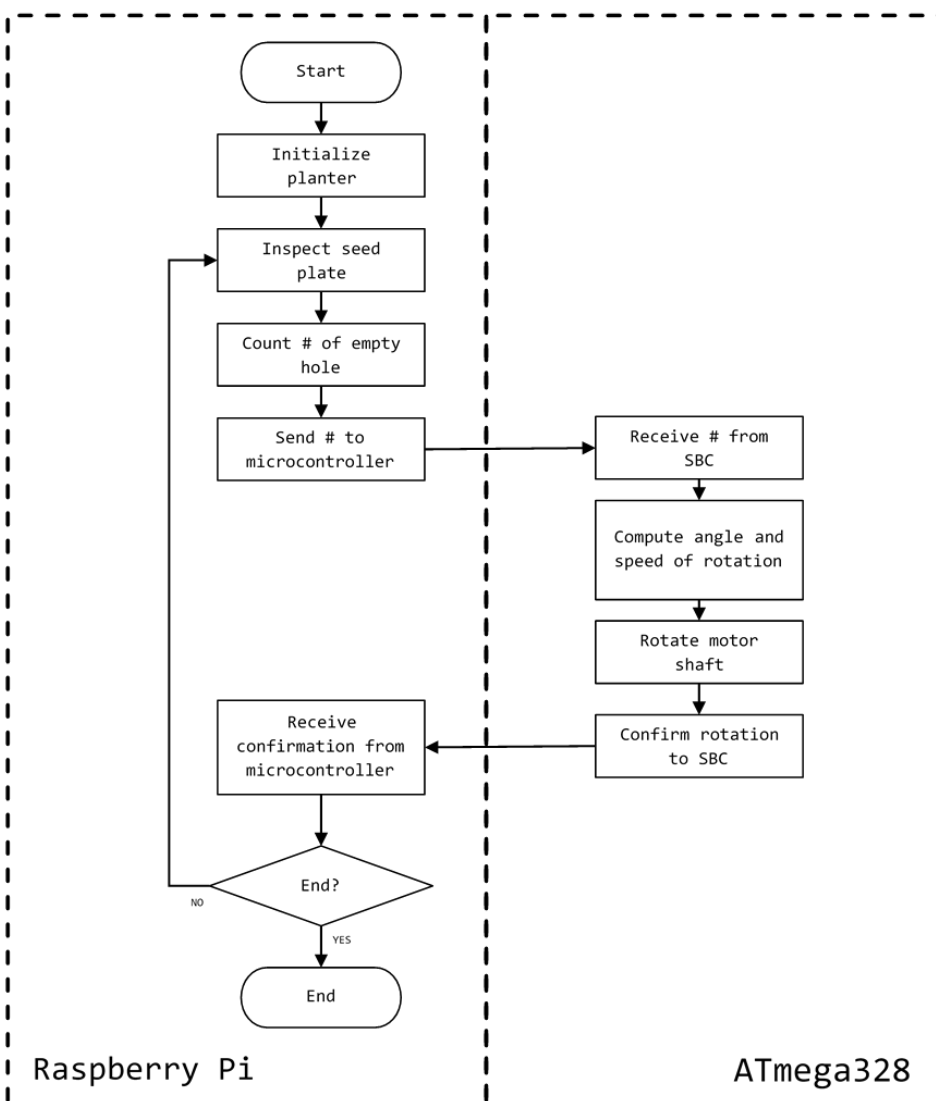

Figure 5. Flowchart of the operation of the planter showing the processes handled by the SBC (Raspberry Pi) and the microcontroller (ATmega328).

drop point. The program loop is illustrated in Figure 5. The SBC handles the image processing of the pictures of the seed plate that are taken by the camera module. The image processing counts the number of holes in the SP that are not filled with seeds. That number is then submitted to the microcontroller to compute for the angle of rotation and the corresponding angular speed. The microcontroller then operates the stepper motor to rotate the SP. Once rotation is done, a signal is sent to the SBC to signal the end of operation of the microcontroller. After that, the SBC again checks the SP for unfilled holes.

Seed Identification and Machine Vision System Program Development

The processing time had to be limited to the least amount of time to maintain near real-time image processing, thus a simple method of extracting seeds attached to the SP was adopted for the MVS. The background in the images captured by the camera module is blue to gray with intensity gradients due to low light and the concentration of light at the center of the image. The foreground corn seeds, on the other hand, are yellow in color. Due to low quality of images, the foreground at times may not be fully distinguished from the background. In theory, to separate the background from the seeds, the images need to be converted into grayscale and then binarized. Binarizing requires distinct intensity difference between background and foreground but with the quality of images captured by the camera, additional preprocessing is done.

The additional steps in processing images are described in the workflow shown in Figure 6. Gray pixels can be decomposed into equal levels of red, green and blue components. Yellow pixels have relatively higher levels of red and green components compared to blue. This means that to identify the foreground from the background, only the red and green channels are needed to be considered. To reduce the intensity of the background, the blue channel of the image can be used to reduce the intensity of the background without considerably affecting the intensity of the foreground. This can be done in the image by splitting the image into its component red, green and blue channels. the original raw image can then be converted to grayscale. This single channel image can be processed with the blue channel. The values of pixels from the blue channel can be subtracted from the grayscale to reduce the intensity of the background without affecting the foreground. Otsu (1979) threshold algorithm is then used to binarize the image to provide a dynamic method of thresholding the images captured by the camera as the camera tend to adjust the light intensity overtime. The resulting binary image is usable for seed identification.

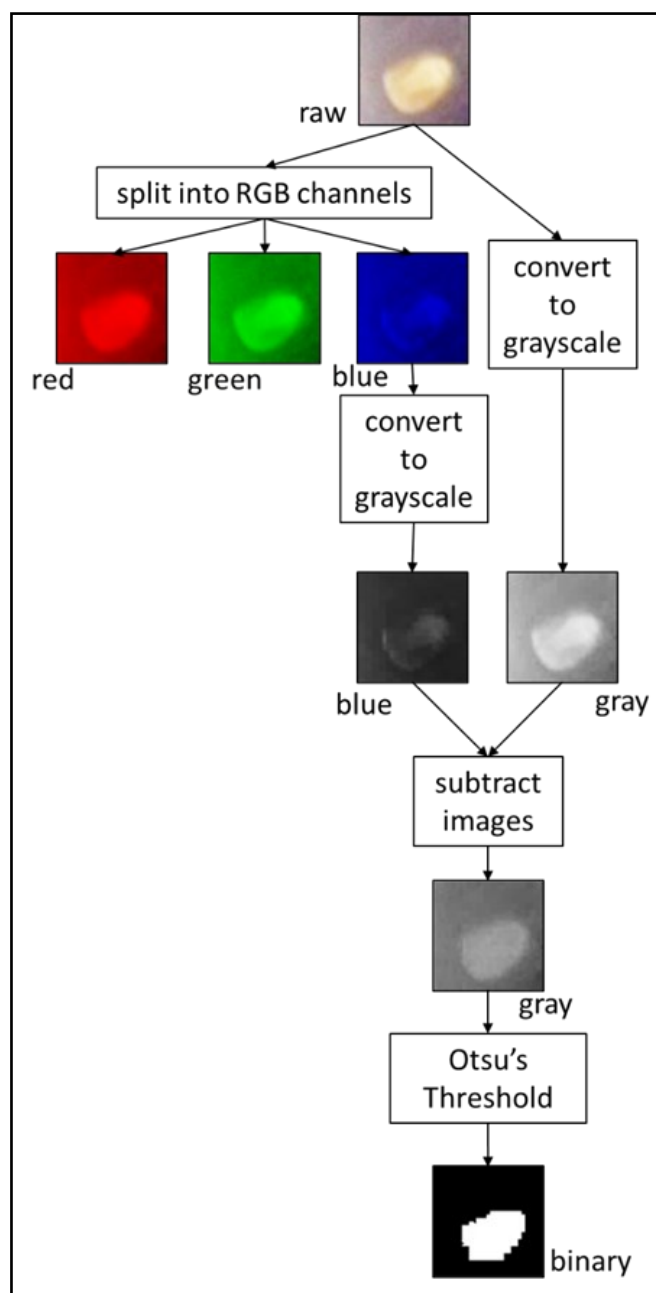Figure 6. Block diagram showing steps for extracting foreground seeds from seed plate background.

Predetermined positions of holes in the image are then inspected if seeds are present in them. A region of interest (ROI) is selected from around each position. Each ROI is inspected if it contains sufficient white pixel blobs. If a sufficiently large blob is identified, the program declares that the

ROI contains a seed. The number of ROIs with no seeds are counted from the right most edge of the visible area. If no ROI was found to be void of seed, the SBC will send a value of 1 to the microcontroller. If unfilled holes were found, a number, $r + 1$, where r is the number of successive ROIs with no seed detected, is sent to the microcontroller.

Preparation of Angular Displacement and Agular Speed Control for the Microcontroller Program

For the planter to be able to deliver seeds at equal spacing, it should be able to drop seeds within a uniform time of operation regardless of the angular displacement that is needed to cover. The time of operation, t, can be defined using Equation 1.

$$t = \frac{\theta}{\omega} \qquad \textit{Equation 1}$$

where, t is the operating time, θ is the amount of angular displacement needed, and ω is the angular speed

Based on that equation, any number, i, multiplied to both θ and ω will not affect the time. The relationship can be defined by Equation 2. The number i is given by the number of holes that should be moved to place a filled hole in the drop point. Any value of i can be multiplied to the numerator and denominator to both increase without affecting the operation time.

$$t = \frac{i\theta}{i\omega} \qquad \textit{Equation 2}$$

where, t is the operating time, θ is the amount of angular displacement needed, ω is the angular speed, i is given by the number of holes that should be moved to place a filled hole in the drop point.

The torque produced in the shaft of the stepper motor is inversely proportional to the rpm of the shaft. This means that increasing the rpm to certain levels will cause the shaft to stall. One solution to this is to prime the shaft rotation at low rpm and slowly increment it until it reaches the desired rpm. The slow rpm phase will increase the total operation time. To counter this, the maximum rpm should be increased. The goal is to achieve the desired θ within a fixed t.

The microcontroller program adjusts the rpm of a stepper motor by adjusting the frequency of signal or the delay between changes in signal level – HIGH and LOW. Each state change translates to a step or an incremental angular displacement of the stepper motor shaft. The length of delay has an inverse relation to rpm. To perform the said adjustments, the delay used for state switching should be adjusted accordingly. The pattern that best describes this is a fourth-degree polynomial equation described in Equation 3.

$$y = m(x + a)^4 + b \qquad \textit{Equation 3}$$

where, y is the length of delay, x is the amount of steps needed, m is the value that determines the steepness of the decrease of y, a is the number of the steps where y is at minimum, b is the smallest value of y.

The x values represent the progression of steps during one operation, the y values represents the length of delay and the area under this curve is the total duration of one operation. If the area of the curve is to be equated to the total duration of one operation, then the constants in the Equation 3 can be determined. Integrating Equation 3 from zero to a certain number of desired steps, s, and equating the resulting equation to the total duration of one operation yields Equations 4 to 6. The constants a and m are used by the microcontroller to compute for the length of delay to apply for each step of the stepper motor given the number derived from counting the number of holes in the SP that are needed to move. During each program loop, the microcontroller computes for all the needed values of y and then implements the stepper operation.

$$a = -\frac{s}{2} \qquad \textit{Equation 4}$$

$$y_0 = 5b(t - 4) \qquad \textit{Equation 5}$$

$$m = \frac{20(y_0 - t)}{s^4} \qquad \textit{Equation 6}$$

where, *a* is the number of the steps where delay is at minimum, *s* is the desired number of steps; y_0 is the initial value of delay; *b* is the smallest value of delay, *t* is the value of delay if the shft rotation was set to a constant; *m* is the value that determines the steepness of the decrease of delay.

Evaluation of the Seed Meter

Tests were conducted to determine the performance of the seed meter. Yellow corn seeds were used for the tests. Three tests were conducted to assess the planter. The first test was done to see if the MD is capable of reliably delivering seeds at uniform intervals. The second was conducted to check the accuracy of the MVS in identifying filled and unfilled holes. Lastly, the third test was conducted to determine if the combined MVS and MD produce less missed seeding compared when no MVS is applied.

Simulated planting speed for the laboratory test rig

The constructed SM was mounted on stationary laboratory test rig. The test rig was used to reduce the unknown factors that may affect the SM's operation. The speed of operation of the SM is a major factor in assessing the performance of the developed seed meter. It is directly related to the speed of a tractor used for actual planting operation. The measure of planting operation speed can be expressed in terms of tractor forward speed (kph); however, since the SM was mounted on a stationary platform,

planting speeds were only simulated by varying the rpm of the SP depending on the desired planting speed. Three planting speeds – 2kph, 4kph, and 6kph – were considered following the findings of Borja *et al*. (2018).

Faux seed test material preparation

Faux seeds were used as samples for tests on the accuracy of the MVS and the reliability of seeding rate of the MD. This was done to purely assess the timing control and the accuracy of the program without being affected by forces acting upon the seeds and the SP. Faux seeds were prepared by randomly selecting 50 seeds using the fishbowl method from 15 kg of yellow corn seed samples. The area of the bounding box of each seed was measured and was later used to create two strata, large seeds (>100mm^2), and small seeds (<100mm^2). Stratified random sampling was done to select 26 seeds from the set – 13 seeds from each stratum. The selected seeds were scanned, printed, and cut-out. This was used as the random set of faux seed samples. The scanned image of the seed samples are shown in Figure 7. The largest scanned seed was enlarged to 1.5 times its original size and 26 copies were printed. This served as the uniform set of faux seeds, which consisted of a uniform set of large seeds that the MVS can easily identify.

Test for the seeding rate reliability of the Mechatronic Drive

The uniform set of faux seeds were used to determine if the MD can effectively deliver seeds

Figure 7. Scanned image of seeds arranged from largest (sample 1) to smallest (sample 26) selected for creating faux seed samples.

to the seed scraper. The use of a uniform set of faux seeds reduces the effect of the performance of the MVS of the SM. Faux seeds were attached to the holes of the SP following the patterns shown in Figure 8. The number of empty holes in the SP is related to the multiplier factor, i, used by the microcontroller. Four (4) conditions were investigated: filled SP (P0); an alternating pattern of one empty hole followed by one filled hole (P1); an alternating pattern of two empty holes followed by 1 filled hole (P2); an alternating pattern of three empty holes followed by 1 filled hole (P3). Each pattern was tested at varying planting speed settings – 2kph, 4kph, and 6kph. The SM was operated until 300 faux seeds were read by the MVS. The period it took to move one filled hole towards the drop point, in seconds, was recorded. The data were retrieved from the command line terminal, wherein the program displays each data point every time it ends its operation. The pattern which had all the holes in the SP filled with faux seeds (P0) was used as the control.

(a) Pattern 0 (P0)   (b) Pattern 1 (P1)

(c) Pattern 2 (P2)   (d) Pattern 3 (P4)

Figure 8. Patterns used for each treatment used for assessing the mechatronic drive

Test for the accuracy in identifying filled and unfilled holes of the Machine Vision System

The accuracy of the system in discerning filled and unfilled holes in the seed plate is important in determining if the image processing workflow of the program is reliable enough to be used as the basis for the decision-making process of the system. The system is expected to perform at different forward speeds. The performance at different speed settings may affect the accuracy of the system.
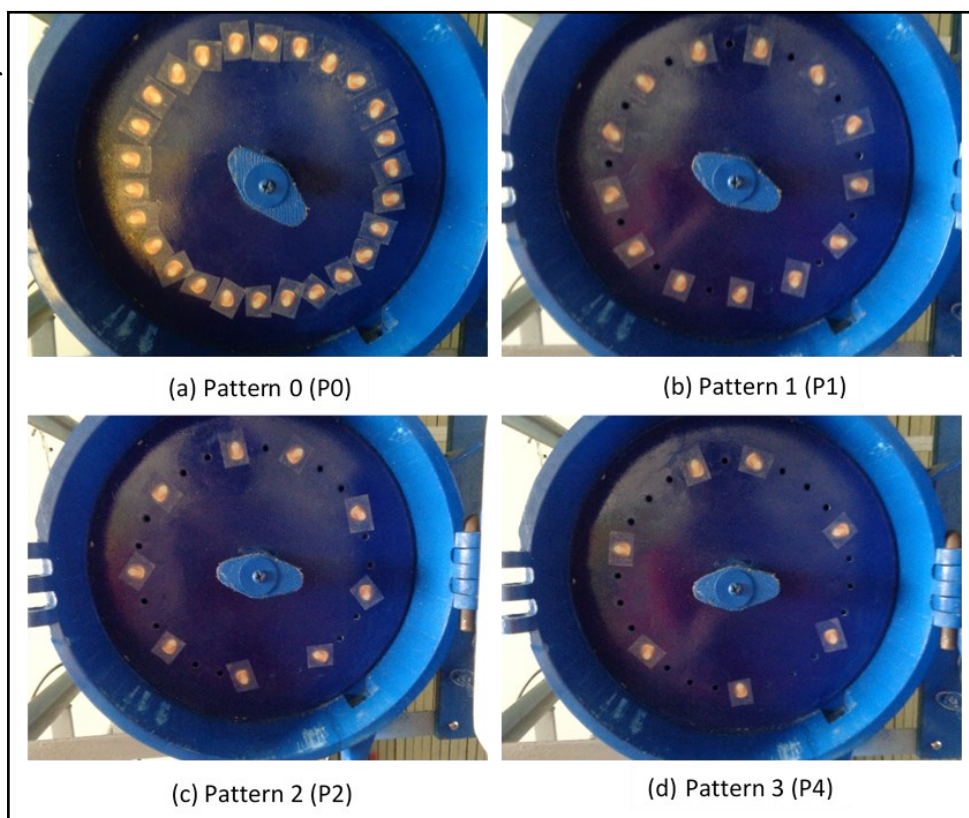
Ten (10) patterns of faux seed layout were applied to the seed plate holes. The layout patters used are shown in Table 1. One of the random layout patterns on the seed plate is shown in Figure 9. The designation of faux seed sample to their corresponding hole number was set at random. The presence or absence of a faux seed in a hole was also randomized. All patterns generated were limited to only have a maximum of three (3) consecutive empty holes. These 10 patterns were subjected to the machine vision system at varying speed settings (2 kph, 4 kph and 6 kph) for one full rotation of the seed plate. Each of the holes were checked by the MVS program once. The dependent variable of interest in this test was the percent error (% error) of the total readings per pattern which was computed following Equation 7.

$$\%error = \frac{e}{n} \times 100\%$$ ***Equation 7***

where, e is the number of false positive or false negative readings, and n is the number of readings performed

Test for the effectiveness of the Machine Vision System and Mechatronic Drive in reducing missed seeding incidence

A multi-factor experiment was designed to assess the capability of the SM with MVS in maintaining a uniform seed rate at the seed tube. In this test, the SM was operated, and actual yellow corn seeds were fed into the hopper. The SM was tested at three (3) planting speed settings (2kph, 4kph and 6kph) and at three (3) hopper fill levels (¼ full, ½ full and ¾ full). Hopper fill can affect the flow of seeds into the chamber inside the meter. It can influence the pickup of seeds by the SP as the level of fill can be related to the compaction of seeds inside the meter. The increase in compaction can lead to difficulty in picking seeds. The hopper had a total capacity of 6.55 kg of corn seeds, thus, the said hopper fills corresponded to 1.64 kg, 3.27 kg, and 4.91 kg of corn seeds, respectively. These levels were maintained throughout the conduct of the test.

Table 1. The random patterns (labeled R1 to R10) used for assessing the accuracy of the MVS in discerning filled and unfilled holes in the SP.

HOLE #	SAMPLE#	PATTERN									
		R 1	R 2	R 3	P 4	R 5	R 6	R 7	R 8	R 9	R 10
1	5	1*	0*	1	0	1	0	0	1	0	0
2	2	0	0	0	0	1	0	0	0	0	1
3	10	1	1	0	0	0	1	1	0	1	0
4	21	0	0	0	1	0	0	0	0	1	1
5	14	0	0	1	0	0	0	0	1	1	0
6	23	0	1	0	0	1	0	1	1	0	0
7	8	1	1	0	1	1	1	0	0	0	1
8	6	0	0	1	0	0	1	1	1	1	0
9	7	0	1	0	1	0	1	0	0	0	0
10	26	1	0	0	0	1	0	0	0	1	1
11	25	1	1	1	1	1	0	1	1	0	1
12	12	0	0	1	0	1	0	0	0	1	0
13	19	1	0	0	1	0	1	0	1	0	1
14	24	1	0	0	0	0	0	0	0	0	0
15	22	0	1	0	0	1	0	1	1	1	0
16	4	0	0	1	0	0	1	0	0	0	0
17	3	0	1	1	1	0	1	1	1	0	1
18	20	1	1	0	0	1	0	0	0	1	1
19	18	0	0	0	0	0	1	0	1	0	0
20	16	1	0	0	0	1	0	1	0	1	1
21	9	0	1	1	1	0	1	0	0	0	0
22	13	0	1	0	0	1	0	1	1	1	1
23	11	0	0	0	1	1	0	0	1	0	0
24	1	1	1	0	1	0	0	0	1	0	0
25	17	0	0	1	0	0	1	0	0	1	1
26	15	1	1	0	0	1	0	1	1	0	0

*1 – seed present; 0 – seed absent

To evaluate the effectiveness of the MVS in controlling the rate of seed release, two (2) experimental setups were compared, a setup with MVS enabled and a seutup with MVS disabled. The latter runs the drive of SP at a constant rotation corresponding to the speed settings. The SM was operated and allowed to drop 301 seeds for each speed setting and hopper fill combination for both experimental and control setups. A seed drop sensor was installed at the end of the seed tube and the interval between each seed drop was measured. This method produced a total of 300 seed drop intervals for each treatment. The intervals of each drop were logged and displayed in the Serial Monitor of the Arduino IDE, which was later recorded for data processing and analysis.
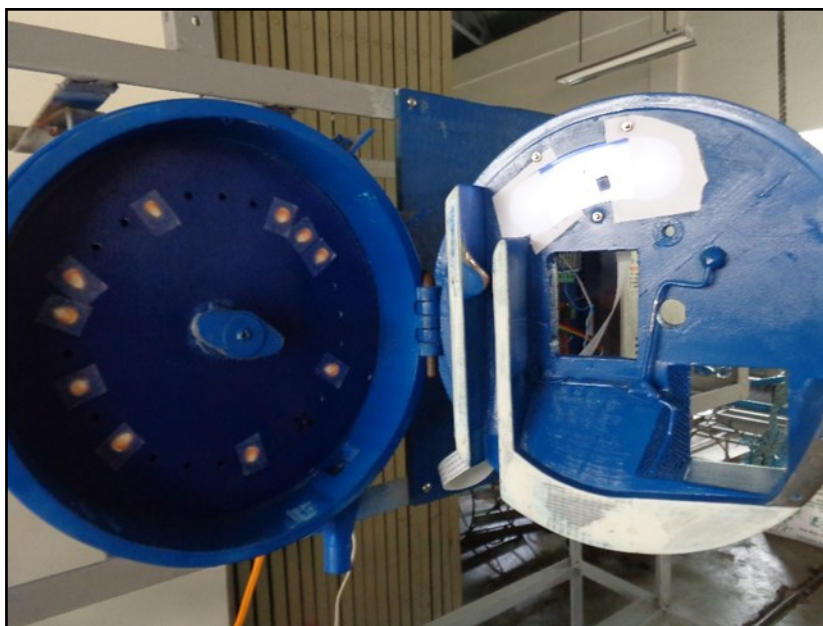

Figure 9. Faux seeds arranged in random layout for accuracy test.

The interest for this test was to determine if the operation type (use of MVS), the forward speed setting and the hopper fill level, had significant effects on the performance of the SM. The H0, which states that the means of time intervals between seed drops across treatments are equal, was tested using a 3-way Analysis of Variance (ANOVA). Rejecting the H0 means that the alternative hypothesis is accepted, which states that at least one of the means is significantly different from the rest. A rejection of the H0 will mean that the factors in consideration can produce a significant effect on the performance of the planter.

Estimating the Number of Missed Seeding Incidence

In evaluating precision planters, several parameters should be investigated. This includes multiple index, missing index, feed quality index and coefficient of variation. Among these, Missing index (MI) is commonly used to assess the incidence of MH during planter operation. MI was used by several research works including the studies on precision planter studies of Searle et. al (2008), Önal et. al (2010), Miller et. al (2012), Yazgi et. al (2014), Song et. al (2014), Li et. al (2016) and He et. al (2017). When evaluating a planter either in the field or in the laboratory using a sticky belt setup, MI can be simply defined by Equation 8.

$$MI = \frac{n_0}{N} \times 100\% \qquad \textbf{\textit{Equation 8}}$$

where, *MI* is the missing index, *N* is the total number of seed spacing readings, and n_0 is the number of spacing greater than 1.5 times the theory seed spacing

The formula considers any seed spacing greater than 1.5 times the theory seed spacing as one missing hill. A problem on this method occurs when the seed spacing is large enough to fit more than one hill within it, as that seed spacing will only be considered as one missing hill based on the definition of a "missing hill". This scenario will occur when the SP at the time of planting had consecutive unfilled holes in the SP. Since the SM was designed to reduce the effect of such scenarios on the hill spacing, another evaluating parameter had to be devised to account for this ability of the SM.

One way to provide a quantitative value for the performance of the planter is to have a direct count on the committed MH of the planter based on the planting distances. This can be achieved by dividing large planting distances by the expected theoretical planting distance. The problem with using the theoretical planting distance is that it ignores variables that affect the planting distance. One possibly good value for planting distance is the average hill spacing of the population. The problem with this value is that it is highly adulterated by the hill spacings containing MH and hill spacings between multiples. The collected data, however, can be easily sorted to extract a value for computing the number of MH committed by the planter. This process is detailed in Figure 10. This was adopted for the evaluation of the planter. For each trial, 301 seeds were dropped by the planter to achieve a total of 300 drop interval data points. The time interval of each drop was recorded and used as primary data for this test.

The first step in processing the data was to identify the intervals that were greater than 1.5 times the overall mean interval. After which, the average of all values that passed the initial screening was taken. A new average was calculated and a new definition for intervals with MH was created. The set was then rescreened. This time, the screening included the removal of intervals of multiples. The average of the new set was again computed. This was repeated once to make sure that the average of the set did not contain intervals with MH and intervals of multiples.

Each eliminated interval that contained MH were divided by the average interval computed from the previous step. The resulting values were truncated from their fractional components and then summed. This was considered as the number of MH committed by the planter. Then the eliminated intervals of multiples were counted and subtracted from the sum of committed MH. This is in consideration that some of the seeds intended for the MH dropped close to the next or previous seed hence they should not be counted as missing. The resulting value represented the number of MH committed by the planter during operation.
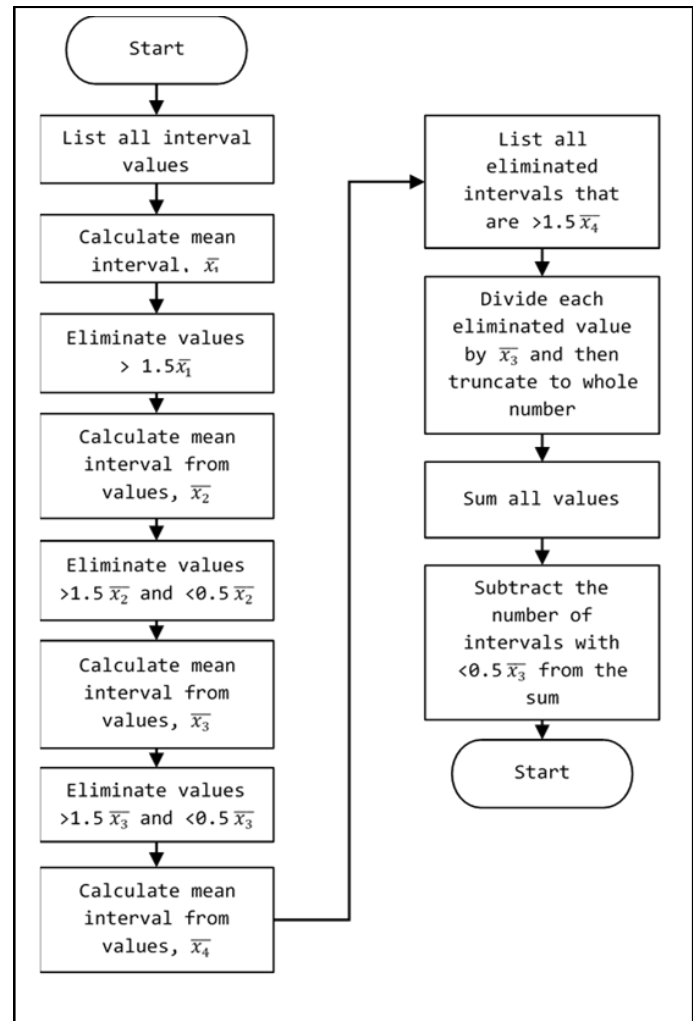

Figure 10. Faux seeds arranged in random layout for accuracy test.

RESULTS AND DISCUSSION

Evaluation of Reliability of Seed Delivery of the Mechatronic Drive

A total of 3,600 data points, which were the periods taken to move seeds toward the drop point, were collected from running the planter using four (4) patterns of faux seeds (P0, P1, P2, P3) in the SP. The average of each run was calculated and summarized in Table 2. The mean period needed for moving seeds toward the drop point for each applied pattern at 2kph speed setting were tested using a one-way ANOVA test (between-subject factor) at alpha equal to 0.05 to determine if each

of the data suggests equal means for all treatments. Analysis of data revealed that the mean value for 299 seed drop intervals for each pattern varied. Further inspection and pairwise comparison of the patterns showed that the treatment means are significantly different from each other. The same case was observed after analyzing the gathered data for every applied pattern at 4kph and 6kph speed settings. The summary of ANOVA tables are shown in Table 3.

Based on the results, the time it took to move one seed towards the drop point was different for each faux seed pattern at any given speed setting. Each pattern represents a scenario that would trigger an increase in rpm of the stepper motor shaft. The test revealed that the drive was not capable of reliably maintaining a uniform rate of seed discharge.

The pattern P0 simulated an ideal performance for the SP where the planter filled all holes in the SP. The drive movement for this pattern can be used as a base value for assessing the movements caused by the rest of the patterns. Patterns P1, P2, and P3 caused one-hole skip, two-hole skips and three-hole skips, respectively. Taking the difference between the values under P0 in Table 2 and values under P1, P2 and P3 with respect to their corresponding speed settings yielded the values presented in Table 4. These values represent the time difference between normal operation movement and operations that require hole skipping. It can be observed in Figure 5 that the number of skips made is linearly proportional to the time difference. The correlation between the number of skips and the time difference is strong as suggested by the Pearson Correlation Coefficients (0.9657, 0.9958 and 0.9265) for each speed setting (2kph, 4kph and 6kph). This means that as the amount of movement needed to deliver seeds increases, the larger the deviation from the normal movement will be.

In theory, the number of processes used by the MVS for identifying the patterns in the SP remains the same regardless of the pattern, thus the time

Table 2. The mean period – in seconds – needed for moving seeds toward the drop point at different forward speeds and SP patterns.

FORWARD	P0	P1	P2	P3
2kph	0.5080	0.5657	0.5956	0.6237
4kph	0.2997	0.3333	0.3630	0.3880
6kph	0.2006	0.2646	0.2960	0.3140

Table 3. Summary of ANOVA table for three simulated planting speed settings – 2kph, 4kph, and 6kph.

SETTING	SOURCE OF VARIATION	SS	df	MS	F	P-value	F crit
2kph	Between Groups	2.20634	3	0.73545	2313.49	0	2.61234
	Within Groups	0.3802	1196	0.00032			
	Total	2.58655	1199				
4kph	Between Groups	1.3066	3	0.43553	1361.01	0	2.61234
	Within Groups	0.38273	1196	0.00032			
	Total	1.68933	1199				
6kph	Between Groups	2.23443	3	0.74481	1674.63	0	2.61234
	Within Groups	0.53193	1196	0.00044			
	Total	2.76636	1199				

difference between the mean move time of skip-less movements and n-skip moves cannot be attributed to the SBC. The only factor that varied accors the different patterns during operation was the number of computed delay values, which is calculated by the microcontroller, thus the time differences are attributed by the latencies during processing of input data in the microcontroller. The latency in the microcontroller occurred when function in the program calculates the delay used for producing the pulses needed by the stepper motor driver.

For regular movements that do not skip holes, the number of calculations needed to compute for the delay pattern is relatively small. As the number of steps needed to move holes increases, the number of calculations also increases proportionally. For example, the needed number of delay values for moving hole 0 to hole 1 is 82 values. If hole 1 is to be skipped and the move will be from hole 0 to hole 2, then the number of delays to be computed will be 164 values, which is twice the first value. The number increases by 82 steps for each hole skipped. This means that for the drive to skip 2 holes and 3 holes it would need to calculate 246 and 328 values, respectively.

The problem could have been avoided if the values for delay were predetermined or have been calculated before hand. All possible values needed can be computed during the initialization and stored in the memory. The number of values of delay is dependent on the total delay needed. Since the total delay is dependent on the processing time of the SBC it can have several to a hundred values. For example, the total delay has 100 different values, and each total delay value will have four levels of movement depending on the number of holes to skip. Each total delay value will have 82 zero skip delay values, 164 single skip delay values, 246 double skip delay values, and 328 triple skip delay values. There will be a total of 820 delay values for each total delay value or a
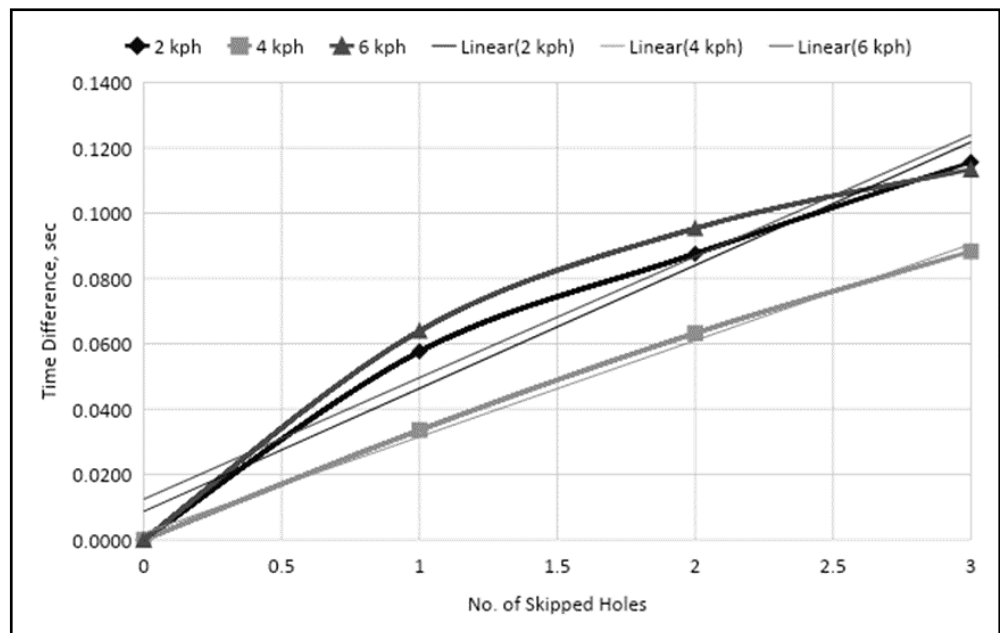

Figure 11. The relative increase in the time interval of drops with respect to the increase in the number of holes skipped.

Table 4. Time difference between the mean move time of skip-less movements and n-skip moves at different forward speeds.

SIMULATED PLANTING SPEED	0 SKIP	1 SKIP	2 SKIPS	3 SKIPS
2kph	0.0000	0.0577	0.0876	0.1157
4kph	0.0000	0.0336	0.0633	0.0883
6kph	0.0000	0.0640	0.0954	0.1134

total of 8,200 delay values for 100 total delay values. Each delay value occupies 2 bytes which means that all values will occupy a total of 164,000 bytes or 160.1563kb. Note that the memory of the microcontroller chip (ATmega32U4) was only 2560 bytes. Such an approach cannot be applied to the current system and a different microcontroller has to be installed.

Assessment of the accuracy of the MVS in Identifying Seeds in the SP

About 780 hole readings were gathered on the test for the accuracy of the MVS in identifying corn seeds in the SP. The MVS at 2kph and 6kph speed settings did not commit any error in identifying corn seeds. At 4kph speed setting, the MVS committed two errors resulting in a 0.7692 % error, which is equivalent to one error out of 130 readings. Taking the value for percent error for all the data points results in a value of 0.2564 % error or one error committed out of 360 readings.

The accuracy in discerning seeds can be attributed to the technique used for processing the images captured by the camera. This technique involved color channel manipulations and dynamic global thresholding (Otsu's Thresholding Algorithm) to easily remove background retails. The use of Otsu's Thresholding Algorithm was an effective counter for the automatic exposure and gain adjustment feature of the camera that continuously adjusts the brightness and contrasts of captured images.

The two errors committed by the MVS were both false positive detections. Despite the effectiveness of the dynamic global thresholding algorithm in binarizing in images taken using a camera with automatic exposure and gain adjustment feature, it caused the false positive errors. Based on the observation of captured raw images and analysis of Otsu's Algorythm, two conditions must be met for the algorithm to detect false positives. First, light intensity should be at a certain low level and second, there should be no intensity gradient in the background and foreground. Low light causes the camera to capture overexposed images when no sufficient intensity gradient is detected. For normal SP images, the gradient is caused by the presence

of a seed in the image. The edge of the seed has a high gradient due to the transition of color from gray or blue to yellow or white. These overexposed images contain pixels that do not represent the true color of the image. These pixels come from areas of the image that have a slight light reflection. Due to overexposure, these slight light reflections become amplified. The problem with this is that these amplified colors tend to become noisy. These noises cannot be removed by the technique used in manipulating color channels. Otsu's Thresholding Algorithm will consider these noises to be part of the foreground and retain them. If the resulting noise pixel blobs are large enough, they will be considered as seeds, thus committing a false positive detection.

Evaluation of the Performance of Machine Vision System and Mechatronic Drive in reducing the committed missed seeding of the Seed Meter

A total of 5,400 data points were collected for the multifactorial experimental design that was conducted to test the performance of the seeder. The distribution of the seed drop intervals for each of the treatments with are shown in Figure 12.

After analyzing the raw data of seed drop intervals using 3-way ANOVA, it was observed that the combined effect of all three factors (Forward Speed × Hopper Fill × Operation Type) did not show a significant effect on the performance of the planter or at least one of the factors does not have a significant effect on the performance of the planter. Further inspection into each of the paired combinations of the factors shows that both Forward Speed × Operation Type combination and Hopper Fill × Operation Type combination had significant effects on the performance. Only the Forward Speed × Hopper Fill combination did not prove to be significant. This implies that one of the factors does not have any significant effect on the performance of the planter. The individual factors show that the insignificant factor is the Hopper fill. The summary table of the 3-way ANOVA is presented in Table 5.

Knowing that changes in the hopper fill do not significantly affect the performance of the SM

means that the planter will reliably maintain a uniform performance over time. During planting operations, the level of seeds in the hopper gradually lowers over the period of planting. If hopper fill had a significant effect on the performance, a certain level should be maintained by the operation to sustain a consistent performance. Since the condition is otherwise, the operator can expect an even level of performance from the SM during long periods of operation. Eliminating hopper fill from the set of factors for consideration leaves speed and operation type. As the outcome of the statistical test implies, the combination of these factors and each of the individual factors can have a significant effect on the performance of the SM.

The distribution of the committed missed

seeding for each of the treatments with are shown in Figure 13. The control or the performance of the setup without the MVS had mean missing hill incidence per trial of 339, 325, and 299 at 2kph,
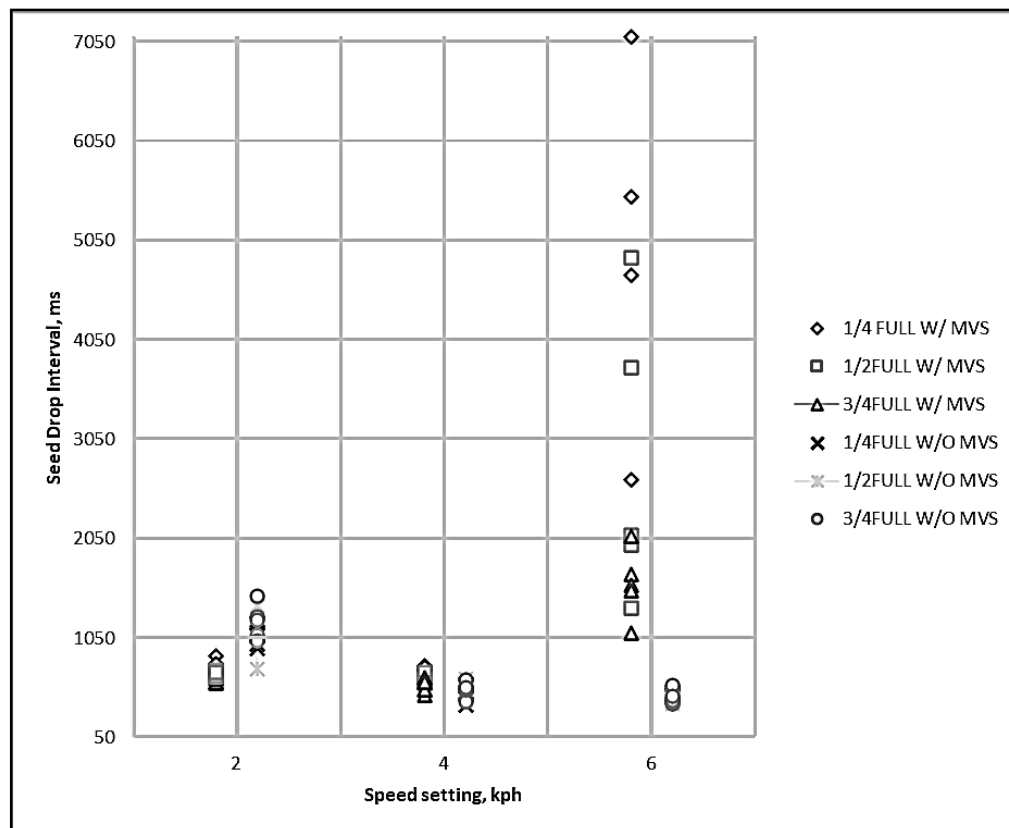

Figure 12. Seed drop interval distribution for 3 speed settings (2kph, 4kph, and 6kph) with 3 levels of hopper fill (1/4 full, ½ full, and ¾ full) using 2 operation setups (with MVS and without MVS).

Table 5. Three-Way ANOVA Summary table showing computed F-values and P-values for each factor and factor combinations.

FACTORS	F-CRIT	F-VALUE	P-VALUE
Forward Speed	$F(2,72) = 3.123907$	106.00	0.000001
Hopper Fill	$F(2,72) = 3.123907$	1.46	0.238801
Operation Type	$F(1,72) = 3.973897$	10.90	0.001482
Forward Speed × Hopper Fill	$F(4,72) = 2.498919$	1.46	0.223726
Forward Speed × Operation Type	$F(2,72) = 3.123907$	139.00	0.000001
Hopper Fill × Operation Type	$F(2,72) = 3.123907$	3.20	0.046665
Forward Speed × Hopper Fill × Operation Type	$F(4,72) = 2.498919$	1.38	0.251008

4kph, and 6kph, respectively. Based on a one-way ANOVA test at 95% level of confidence (Table 6), no evidence was found that suggests that the means of all treatments that did not use the MVS are significantly different from each other. The SM performed consistently when the MVS was not used. This suggests that the seed pickup mechanism of the SP is not sensitive to the SP's rpm.

A statistical comparison (t-Test) was used to determine if the sets of data for the number of committed MH per trial at 2kph simulated planting speed were significantly different when the MVS was used and not used. The means of each dataset were found to be significantly different from each other with a 95% level of confidence. The mean of the dataset obtained from the trials that used the MVS was 146.5000 MH, while the mean of the dataset obtained from the trials that did not use the MVS was 335.2857 MH. This suggests that a reduction in the number of committed MH was observed in the SM that used the MVS at 2kph simulated planting speed.

The same statistical test was performed for the dataset pairs obtained from the trials that were operated at 4kph

simulated planting speed. The test revealed that the means of each dataset were also found to be significantly different from each other with a 95% level of confidence. The mean of the dataset obtained from the trials that used the MVS was 256.8571 MH, while the mean of the dataset obtained from the trials that did not use the MVS was 328.1429 MH. This also suggests that a reduction in the number of committed MH was observed in the SM that used the MVS at 4kph simulated planting speed.
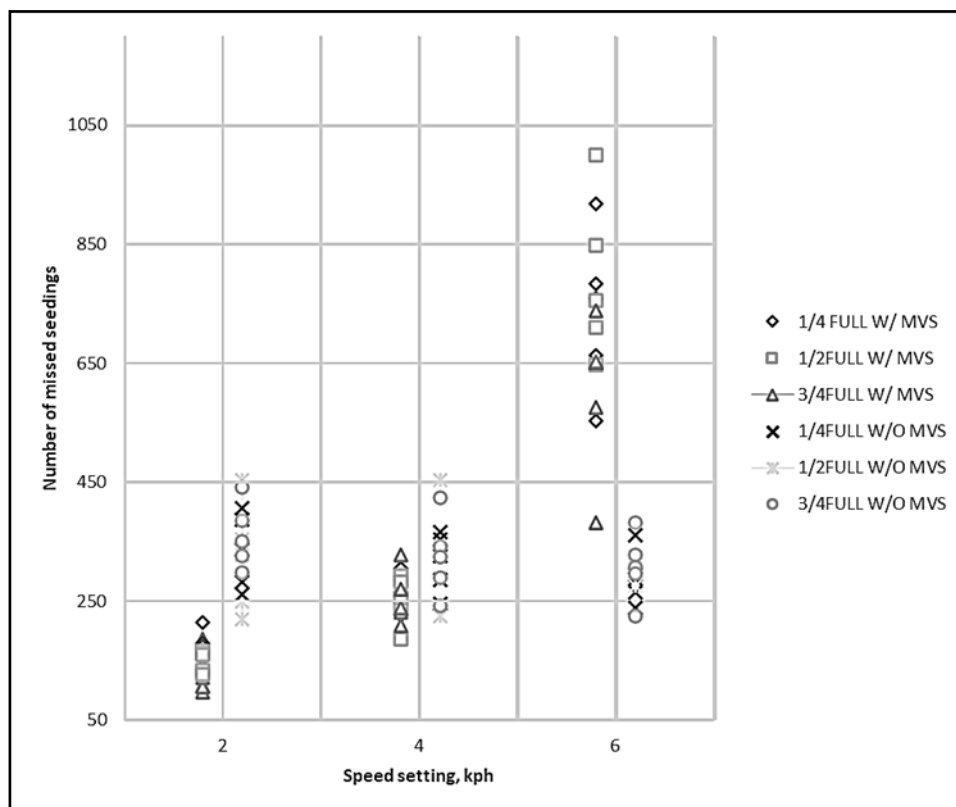

Figure 13. Number of missed seeding distribution for 3 speed settings (2kph, 4kph, and 6kph) with 3 levels of hopper fill (1/4 full, ½ full, and ¾ full) using 2 operation setups (with MVS and without MVS).

Table 6. Summary table of One-Way ANOVA for treatments without the MVS at different planting speed settings – 2kph, 4kph, and 6kph.

SOURCE OF VARIATION	SS	df	MS	F	P-value	F crit
Between Groups	12776.3	2	6388.15	1.98083	0.1498	3.20432
Within Groups	145124	45	3224.99			
Total	157901	47				

For the dataset pairs obtained from the trials that were operated at 6kph simulated planting speed, a t-Test was also used to compare the means of the two datasets. Based on the results of the statistical test, it was observed that the two means were also significantly different at a 95% level of confidence. In these dataset pairs, however, it was observed that the mean of the dataset (703.2857 MH) obtained from the trials that used the MVS was higher than the observed mean of the dataset (300.3571 MH) obtained from the trials that did not use the MVS. This suggests that the use of the MVS at 6kph simulated planting speed produced more committed MH.

The reduction in MH at 2kph and 4kph can be due to the system's feature that adjusts the rpm of the SP whenever it detects unfilled holes. The system does this by increasing the rpm to close the gap between seed drops. This feature, however, also made the system fail at 6kph. Whenever the rpm is increased, two limits are approached. First is the limit for the suction force to hold the seeds into the plate. As the rpm increases, inertia in the seeds will also increase. At a certain level, the inertia will be high enough that the suction produced by the vacuum will not be able to hold the seeds in place, thus causing seeds to be dislodged from the SP.

The second limit approached is the torque required to rotate the SP. Stepper motors are known to have the highest torque level when at a stop. The torque produced by the shaft decreases as the rpm increases. In the case of the motor used in this study, even though the microcontroller had a feature that allowed a gradual increase in rpm to reduce the impact of inertia, the torque produced during the rotation was not enough to overcome the effect of inertia and friction acting on the SP. As a result, the stepper motor stalls.

CONCLUSION

In general, the study was able to develop a working pneumatic SM with a MVS that can perform well up to 4kph planting speed. Its performance was proven to have a reduced occurrence of MH during planting. Given that planting operations are normally performed up to 4kph, the use of the developed drive and monitoring system can be beneficial in performing planting operations, especially when optimizing the use of planting materials.

The developed MVS for the SM was capable of effective identification of seeds inside the SM despite the poor and variable lighting conditions inside the SM. The technique applied for the image processing provided a simple and fast solution that enabled the system to produce excellently accurate results.

The tests performed for the drive did not deliver positive results but showed points for improvement. Its failure in delivering consistent seeding rate may have been due to the limitations of the components used for the system.

RECOMMENDATIONS

Changing the components or restructuring the design and program will provide more options for solving the ineffectiveness of the drive and improve the planter performance.

Including Multiples Detection

Though the technique used for image processing was sufficient in providing the needed quality of results, further improvement in the technique should be pushed not only to perfect the technique but also to incorporate other functionalities like multiples detection. Performing multiples detection may be done using different image segmentation techniques or Artificial Neural Networks. Using these methods will consume more computer resources, thus will take longer period to process. Applying parallelization may be explored for easing the effect of the added processing loads.

Improving Pulse Pattern for Stepper Motor

The computation for the pulse pattern using a fourth degree equation produced significant lag in the microcontroller that significantly affected the performance of the drive. This problem was

caused by the complexity of computations performed by the microcontroller and the memory limitation of the microcontroller. There are three possible solutions to this problem. First is to convert all the floating-point computations to integer computations. This will reduce the resolution of the computation but will reduce the computation time. Second is to device a new method of generating pulse pattern that will be simple and will not consume too much resources. The third option is to transfer the computation to the SBC. The SBC can perform the computation faster and store hundreds of precomputed possible patterns.

Increasing the Torque for The Mechatronic Drive

The torque produced by the stepper motor used in the study was too low at high speeds compared to the minimum requirement of the system as the results suggest. There are two options that can be considered for this problem. First is to consider replacing the stepper motor with a larger frame size. A larger stepper motor will produce a larger amount of torque; however, they will be more expensive. Another option is to replace the stepper motor driver with a driver with higher specification. The stepper motor was rated at 4 amps per phase, but the driver used was only capable of producing less than 4 amps per phase. This means that the stepper motor may still produce a higher amount of torque compared to the setup used in the study.

ACKNOWLEDGMENT

LITERATURE CITED

BORJA, A. A., AMONGO, R. M., SUMINISTRADO, D. C., & PABICO, J. P. (2018). A Machine Vision Assisted Mechatronic Seed Meter for Precision Planting of Corn. 2018 3rd International Conference on Control and Robotics Engineering, (pp. 183-187). Nagoya, Japan. doi:10.1109/ICCRE.2018.8376460'

LI, Y., BINGXIN, Y., TAO, C., YIMING, Y., XIANTAO, H., LIU, Q., DONGXING, Z. (2016). Global Overview of Research Progress and Development of Precision Corn Planters. International Journal of Agricultural and Biological Engineering, Vol. 9 No.1 9, 9-26.

LI, Y., XINTAO, H., DONGXING, Z., SONG, S., RUI, Z., & MANTAO, W. (2015). Development of Mechatronic Driving System for Seed Meters Equiped on Conventional Precision Corn PLanter. International Jornal of Agricultural and Biological Engineering, Vol. 8 No.4, 1-9.

MILLER, E. A., RASCON, J., RAUN, W. R., & KOCHENOWER, R. (2012). Evaluation of Corn Seed Vacuum Metering Systems. ASABE Paper No. 12-1337167. St. Joseph, Michigan, United States of America.

ÖNAL, İ., DEĞIRMENCIOĞLU, A., & YAZGI, A. (2010). An evaluation of seed spacing accuracy of a vacuum type precision metering unit based on theoretical considerations and experiments. Turkish Journal of Agriculture and Forestry, Vol. 36, 133-144.

OROZCO, J. C. (2011). Design and Development of a Vacuum Type Multicrop Planter with Focus on Corn Seeding. Philippine Agricultural Mechanization Journal, Vol.18 No.1, 12-27.

OTSU, N. (1979). A Threshold Selection Method from Gray-Level Histograms. *IEEE Transactions on Systems, Man, and Cybernetics, Vol. 9*, 62-66.

SEARLE, C. L., KOCHER, M. F., SMITH, J. A., & BLANKENSHIP, E. E. (2008). Field Slope Effects on Uniformity of Corn Seed. Applied Engineering in Agriculture, Vol. 24 (5), 581-586.

SONG, S., DONGXING, Z., LI, Y., TAO, C., RUI, Z., & XIAOWEI, Y. (2014). Design and experiment of pneumatic corn precision seed-metering. Transactions of the Chinese Society of Agricultural Engineering, Vol.30 No.5, 10-18.

YAZGI, A., & DEGIRMENCIOGLU, A. (2014). Measurement of seed spacing uniformity performance of a precision metering unit as function of the number of holes on vacuum plate. Measurement, 56(2014), 128-135. ■