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Development and Field Evaluation of a Variable-Depth Tillage Tool Based on a Horizontal Pneumatic Sensor Measurement

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Abstract

Soil compaction can be naturally occurred or can be machinery-induced. Subsoiling is often applied to loosen soil compaction and decrease soil strength to levels that allow for root development and growth. Variable-depth subsoiling which modifies the physical properties of soil only where the tillage is required for crop growth has the potential to reduce labor, costs and fuel, and energy requirements. Since this study aimed to perform subsoiling operations with variable depth, the variable-depth tillage (VDT) tool was developed. A pneumatic multi-nozzles sensor has been used to simultaneously predict the depth of a soil layer in three depths (15, 30, and 45 cm), and send a signal to control the depth of the VDT tool. Evaluation of the VDT tool system was performed by two methods namely static and dynamic tests. In static evaluation, the system response time was measured to reach 95% of the proposed depths. The dynamic evaluation of the tool was accomplished in two steps in the field. The amount of fuel consumption and the travel distance of the tool tine to reach the desired operation depth were measured and compared with the common subsoiler (when the depth control was OFF). The average fuel consumption by using the variable-depth tillage tool decreased by 17.36% compared to the constant depth. Furthermore, the pneumatic sensor tine penetrated into the soil perfectly and sent the control signal to the control unit of the VDT tool in real-time, and the VDT tool loosened the soil at the exact depths sent by the sensor.

Keywords: Compacted soil layer, Fuel consumption reduction, Pneumatic sensor, Precision tillage, Variable-Depth Tillage (VDT) tool

Introduction

Soil compaction affects root growth rate and restricts access to water and nutrients for plants, and hence crop yield. A penetrometer with a conical tip as the standard method has been identified to determine a soil strength index in situ (ASAE, 2002) which is time-consuming and highly variable. In recent decades, several researchers have attempted "on-the-go" measurement of soil strength with horizontal soil resistance tools at multiple depths (Alihamsyah, Humphries, & Bowers, 1990; Adamchuk, Skotnikov, Speichinger, & Kocher, 2003; Chung, Sudduth, Plouffe, & Kitchen, 2004; Koostra & Stombaugh, 2003; Sharifi & Mohsenimanesh, 2012; Khalilian *et al.*, 2014; Vernekar, 2015; Meselhy, 2020, Tahmasebi, Hedayatipoor, Gohari, & Sharifi malverjerdi, 2021).

The negative impacts of soil compaction on crop yields can often be removed by subsoiling. Though, this subsoiling operation is often conducted at unnecessarily deep depths wasting energy and excessively loosening surface residue essential for erosion control and alleviating soil quality (Raper, Reeves, Shaw, van Santen, & Mask, 2007). Different soil tillage operations are implemented to decrease soil compaction. In conventional methods, subsoiling requires a high-energy input to loosen the hardpan layer which causes to lack of farmers' interest to do it. A number of the researchers reported that a reduction in tillage depth could save producers significantly if soil compaction was still eliminated (Raper, 1999; Fulton, Wells, Shearer, & Barnhisel, 1996).

Advances in precision agriculture prepare capabilities to vary soil treatment across an agricultural field (Adamchuk, Skotnikov, Speichinger, & Kocher, 2004). Site-specific tillage can modify soil physical properties where the tillage is required for plant growth. Therefore, it attains significant savings in fuel consumption and drawbar power requirements. Site-specific tillage can be accomplished with (1) a real-time sensor or (2) a pre-tillage map technology (Raper *et al.*, 2005; Gohari, Hemmat, & Afzal, 2010). Raper (1999) approximated that the energy cost of subsoiling could be reduced by as much as 34% using variable-depth tillage against uniform depth tillage.

In a study, a device was developed which calculated the proper position of tillage tools relative to the land surface at each point, and the hydraulic operator set its optimum position. The optimum position of tillage tools is calculated by depth control software established for this device, and its input data were depth for root development. Precision deficiency for laboratory tests was 3.3% and 3.83% for depth increasing and decreasing depth, respectively (Fallahi, Aghkhani, & Bayati, 2015).

In another study, it is stated that consumption of fuel could be decreased by 50% via site-specific tillage in comparison to subsoiling the field (Fulton *et al.*, 1996). Also, Raper *et al.* (2007) reported a 35 and 59% major reduction in draft force, and a 27 and 43% reduction in fuel consumption for site-specific subsoiling in medium (35 cm) and shallow (25 cm) depth hardpan plots in comparison to uniform deep (45 cm) subsoiling in the same plots. The concept of variable-depth tillage was investigated by several researchers (Raper, 1999; Gorucu, Khalilian, Han, Dodd, & Smith, 2006; Gohari *et al.*, 2010; Gohari, 2006). Khalilian *et al.* (2002) demonstrated that variable-depth tillage results in a fuel-saving of 28% and an energy savings of 43% as compared to uniform-depth tillage. In another research, GPS-based variable-depth tillage equipment has been developed and validated in the laboratory and the field (Gohari *et al.*, 2006).

Fox *et al.* (2018) developed an "intelligent Plow" which was a system that mount directly on the tractor and continuously measure the depth to the hardpan and adjust the tillage depth. The system not only measured soil compaction data and calculate the depth and thickness of the hardpan layer but also adjust tillage depth on-the-go in real-time. The finding demonstrated that variable-depth tillage operations, reduced fuel consumption by 45% compared to conventional constant-depth tillage.

An experiment was performed in a field to evaluate a technology to determine the tillage depth based on soil penetration resistance at soil different depths. The field experiment area was divided into five plots including no-tillage; uniform-depth tillage at 25, 35, and 45 cm tillage depth; variable-depth tillage. The results presented that the variable-depth tillage system caused a reduction in the fuel consumption rate, power requirements, and operating costs by about 35%, 35%, and 23%, respectively, in comparison to the uniform-depth tillage system, while the actual field capacity for variable-depth tillage system increased about 21% compared to uniform-depth tillage system (Meselhy, 2021).

As mentioned before, uniform-depth tillage applied by the farmers needs fuel costs and higher energy. Variable-depth tillage could be useful in improving production costs. The primary aim of this research was to know if the variable depth tillage is feasible. Besides, the specific objectives of this research were:

- To develop a two-tine tool equipped with variable-depth tillage instruments
- To evaluate variable-depth control of the proposed tool using an on-the-go pneumatic sensor
- To investigate the performance of variable-depth tillage compared to conventional uniform depth tillage
- To determine the effects of variable-depth tillage on fuel and energy consumption.

Materials and Methods

Since the aim of this project was to develop a system that will mount directly on the tractor and continuously measure the depth to the compacted layer and adjust the subsoiling depth. The proposed system should be able to measure soil compaction data, calculate the depth, and adjust subsoiling depth on-the-go for real-time, variable-depth, tillage operations for crop production. This was accomplished by combining two systems "horizontal pneumatic sensor" and "Variable-Depth tillage" described below.

System design

In the first step, the mathematical calculation to design a tine for variable-depth tillage (VDT) was done. Based on the main tine design of the horizontal pneumatic sensor mentioned (Tahmasebi *et al.*, 2021), the tine dimensions of the VDT tool were considered the same as the pneumatic sensor. The shape of the tines was considered vertical and the dimensions were 60*10*2 cm. Then, the tine was modeled in ANSYS software and the stresses and strains are displayed in Fig. 1. The tine was fully fixed at the end edge as a boundary condition, and soil pressure was exposed on the tine by triangle distribution. A 3D triangle mesh with 6 nodes was used for meshing the object via a meshing tool, and the problem was solved by software. As can be seen, the maximum stress was 617Mpa at the end of the tine, the connection point to the chassis which was less than the steel yield stress (Fig. 1a). Since the desired steel was SPK, and by considering a safety coefficient of 1.5, the Von Mises stress was less than the yield stress of the selected steel (1000Mpa). Also, the strain of the tine is presented in Fig. 1b and the degree of deflection of the tine in the face of the soil force was apparent. This finite element method (FEM) results confirmed that the designed structure can work in considered conditions without the probability of failure in the main parts.

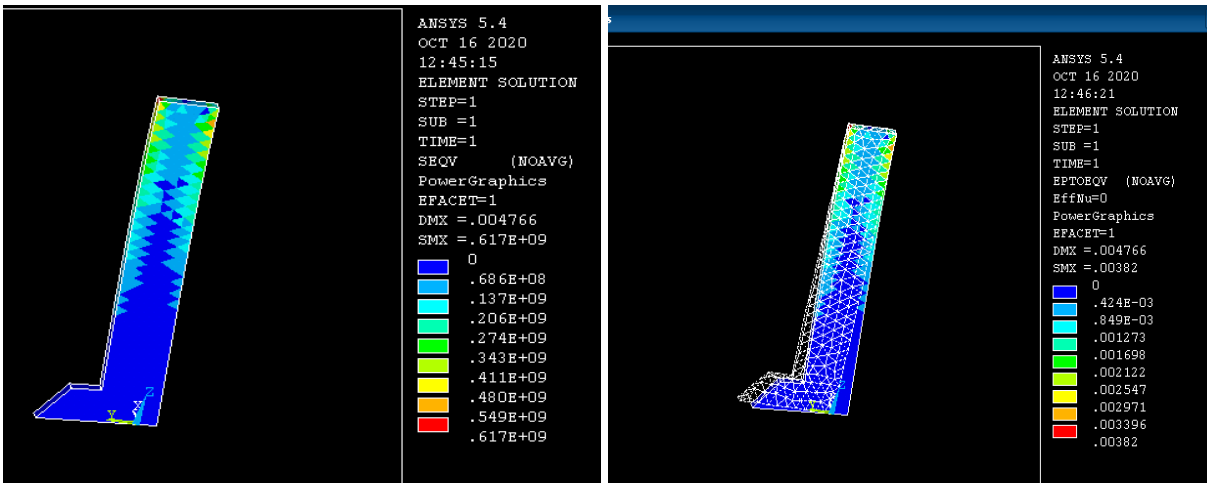

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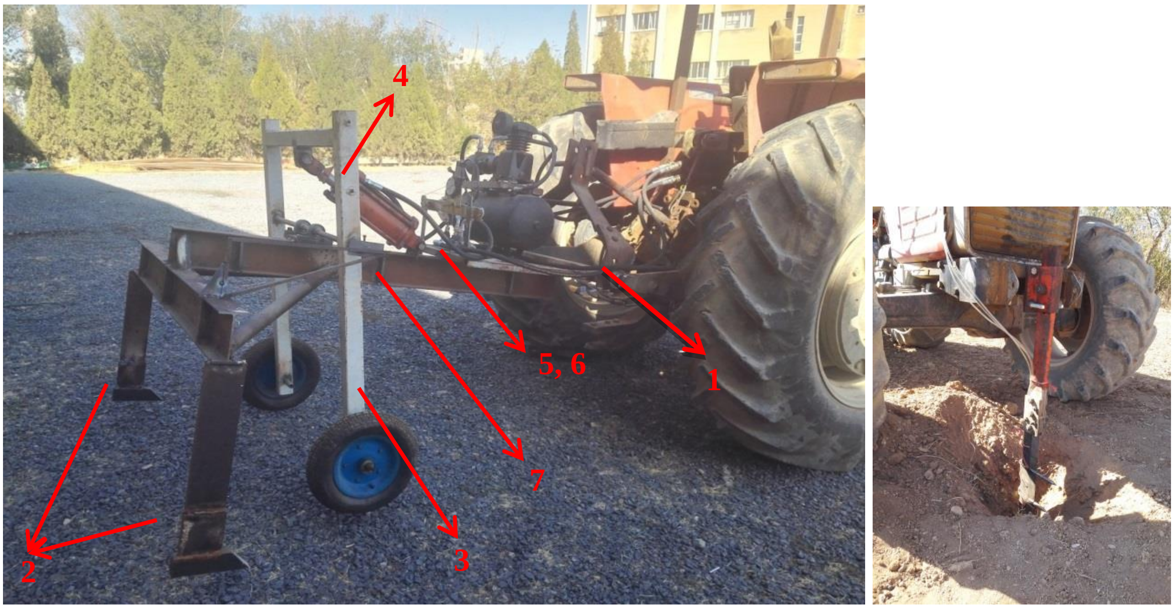
Fig. 1. a) The stresses and b) strains of the VDT tool tine in the ANSYS software

Secondly, an instrumentation system for VDT has been developed and tested (Fig. 1). The main components of the instrumented system consist of 1) main chassis and three-point hitch, 2) tine, 3) wheels and wheel axles, 4) double-sided cylinder, 5) 4/3 Directional control valve, 6) Electric motor pushing hydraulic valve lever, and 7) Shaft encoder (Fig. 2). A horizontal pneumatic sensor was used to measure the mechanical strength of soil at different soil depths (Tahmasebi *et al.*, 2021). The pneumatic sensor equipped with three nozzles with a diameter of 10 mm at three depths of 15, 30, and 45 cm was installed on a tine in front of the tractor to inject air flow into the soil, and the resistance to air permeability into the soil was measured simultaneously.



a

b

Fig. 2. a) View of VDT tool; 1) main chassis and three-point hitch, 2) tine, 3) wheels and wheel axles, 4) double-sided cylinder, 5) 4/3 Directional control valve; 6) Electric motor pushing hydraulic valve lever, and 7) Shaft encoder; b) the pneumatic sensor

In addition, the structure of the VDT tool was modeled in CATIA software which is shown in Fig. 3. It is assumed that the front edge of the tine is perpendicular to the soil surface during operation. The tine was designed with a height of 60 cm while the depth was 45 cm. Since the pneumatic sensor was installed in the front and middle of the tractor, two tines with a distance of 1.5 meters from each other were used for the proposed VDT tool.

System fabrication

After the system design, the proposed VDT tool has been fabricated. Two gauge wheels connected to the hydraulic cylinder were used to adjust the depth of the tools. The VDT tool was connected to the three-point hitch of the tractor (ITM 399).

The maximum depth of the tines was about 45 cm and operation depth ranged from 0 to 45 cm. In order to automatically control the depth of the VDT tool, the opening of two wheels' axle has been controlled by a double-sided hydraulic cylinder with a stroke of 25 cm and a control circuit. The extending speed of the hydraulic cylinder was equal to 0.01 ms^{-1}, and this is due to the existence of multiple orifices and cross-sectional changes in the inlet and outlet of the valve, cylinder, and coupling couplings. The pneumatic sensor including three nozzles installed at three depths of 15, 30, and 45 cm on the sensor tine was used to predict the depth of a soil layer simultaneously (Tahmasebi *et al.*, 2021).

Variable-depth tillage tool pneumatic circuit

The pneumatic circuit diagram for sending the depth control command to the VDT tool system is schematically shown in Fig. 4. All three nozzles injected air into the soil until each of their contact with the hard layer and the pressure inside the pipe connected to it raised above 1.2 bar (threshold).

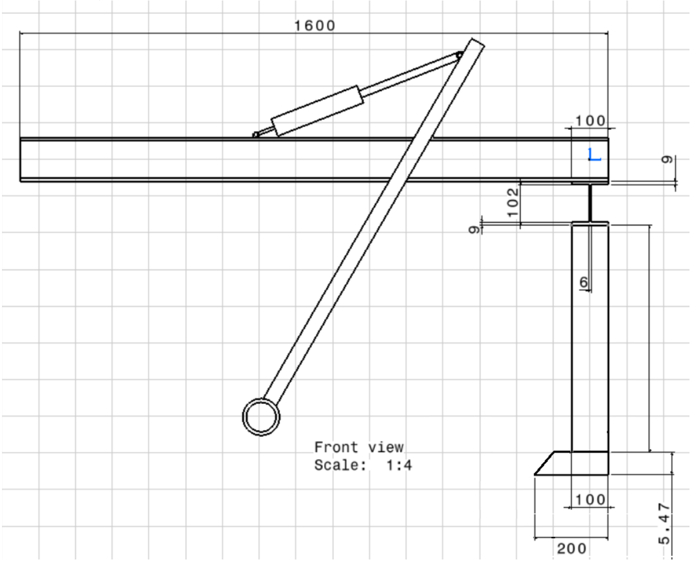


Fig. 3. The initial design of variable-depth tillage tools (units in mm)

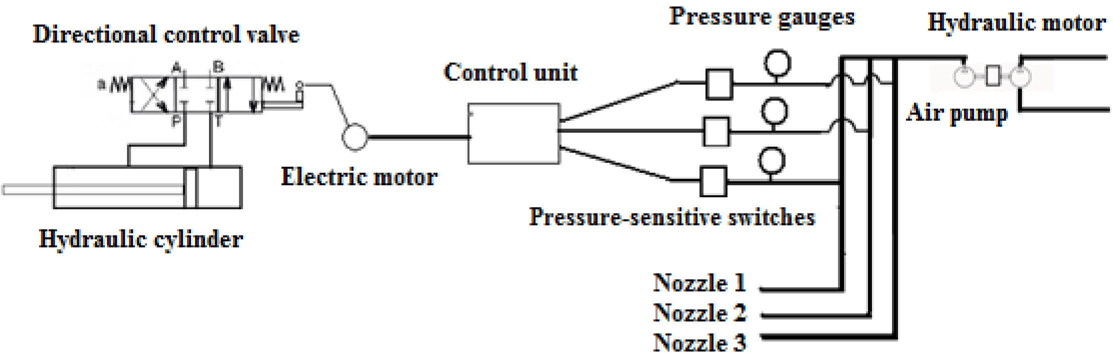


Fig. 4. The pneumatic circuit to send the depth control signal to the VDT tool, including hydraulic motor; Air pump; Pressure gauge; Pressure-sensitive switches; Control unit; Electric motor; Directional control valve, Nozzles, and hydraulic cylinder

At this time, the pressure-sensitive switch that its connection pressure was adjusted to 1.2 bar, was activated and sent the electric current to the electric motor control system that moves the 4/3 Directional control valve. The instrumentation system included three pressure-sensitive switches (RMP-8, one-way with a pressure range of 40-175 psi) as presented in Fig. 5. The lever of the directional control valve was also moved by the control unit, which was closing the hydraulic cylinder connected to the depth control wheel, hence increasing the working depth (Fig. 6). According to the results of Taylor and Gardner (1963) and Alimardani, Abbaspour-Gilandeh, Khalilian, Keyhani, & Sadati, (2007) researches, the threshold of soil compaction based on the cone index is 2 MPa. Therefore, this value according to the research of Clement (2000) and Koostra & Stambuc (2003) was transformed to a threshold air pressure of 1.2 bar for pressure-sensitive switches.

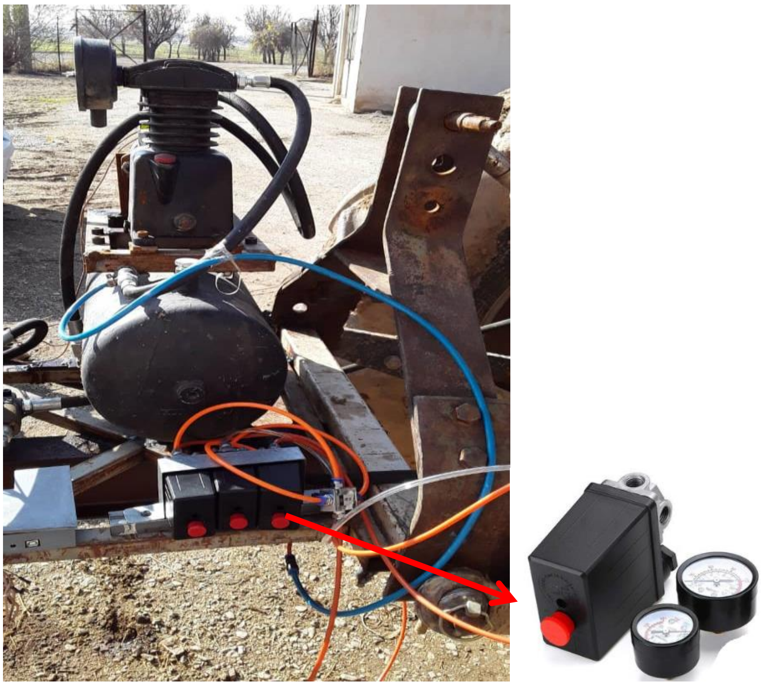


Fig. 5. The pressure-sensitive switches

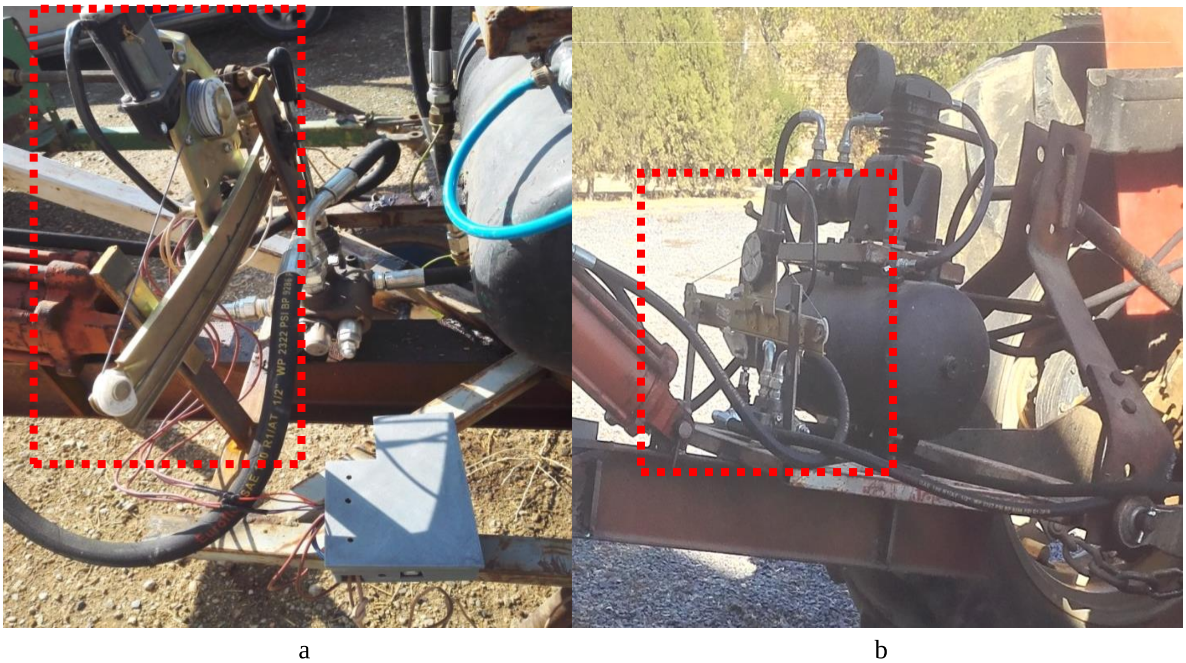


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Fig. 6. a) Electric motor system moving the directional control valve lever; b) 4/3 Directional control valve

Variable-depth tillage tool control unit

As mentioned before, in order to actively control the extending and closing of the cylinder to the desired value, an electronic control unit was developed. In fact, the controller works by settled values, and the type of controller was a lookup table. The operating principles of this circuit are based on the closed-loop and the feedback signal sent from the displacement of the gauge wheel arm, which is shown in the block diagram in Fig. 7. The proposed control circuit consisted of an Arduino (Uno) control board which was programmed. A drive circuit and a voltage regulator were also used to bring the output of the pressure-sensitive switches output to the readable voltage level in the Arduino (Fig. 8). To monitor the depth control and send a feedback signal to the control unit, a 30-pulse rotary shaft encoder (KY-040) was employed to send the instantaneous depth of work by the depth wheel to the control system. Fig. 9 shows the encoder module and installation location on the chassis. A 12-volt electric motor was applied to open and close the 4/3 directional control valve which received the control signal from the control circuit.

Evaluation

Initial testing of the instrumentation system for variable-depth tillage was performed in two phases namely static and field evaluations which will be explained in later sections.

Static evaluation

In the first phase, the static test was accomplished at three depths of 15, 30, and 45 cm, and the control signal was sent to the system and each test was repeated three times. Delay time, rise time, and response time to reach the depth of 95% of the desired depth were obtained by the gyroscope sensor. Angle data of the depth control wheel were acquired after noise filtering by Wavelet Transformation.

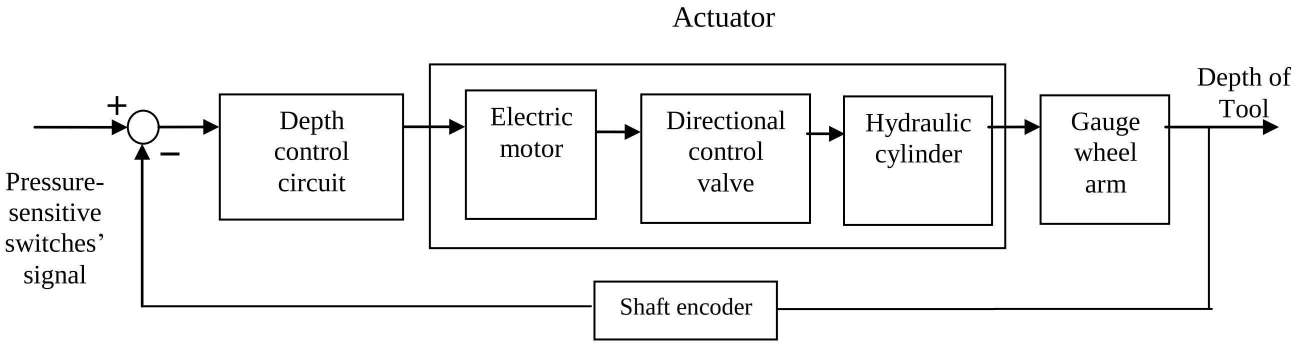


Fig. 7. Block diagram of the control system

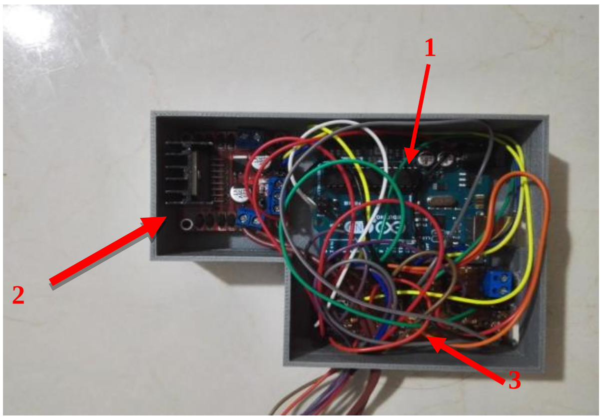


Fig. 8. Electronic control circuit system: 1) Arduino board, 2) Drive circuit, 3) Voltage regulator of pressure-sensitive switches of the pneumatic sensor

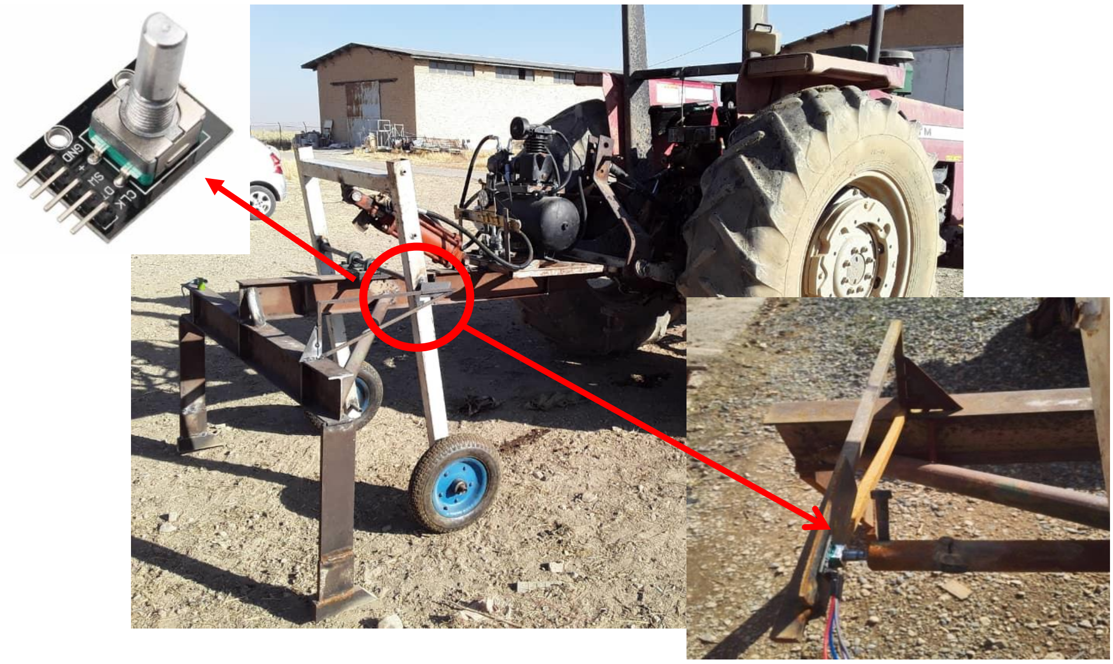


Fig. 9. Shaft encoder and its installation position

Field evaluation

In the second phase, a dynamic test has also been performed in two steps on a no-till field (Markazi Agricultural and Natural Resources Research and Education Center, Iran). A length of 90 m was selected for the main plot which was divided into three subplots of 30 m in length which every 30m was considered a repetition. The soil texture of the field was clay loam and the soil moisture content and bulk density were measured at the three proposed depths in 3 repetitions and the mean values are reported in Table 1 (Tahmasebi *et al.*, 2021). A pneumatic sensor was installed in front of the ITM399 tractor for the determination of soil compaction, and a VDT tool was installed behind the tractor.

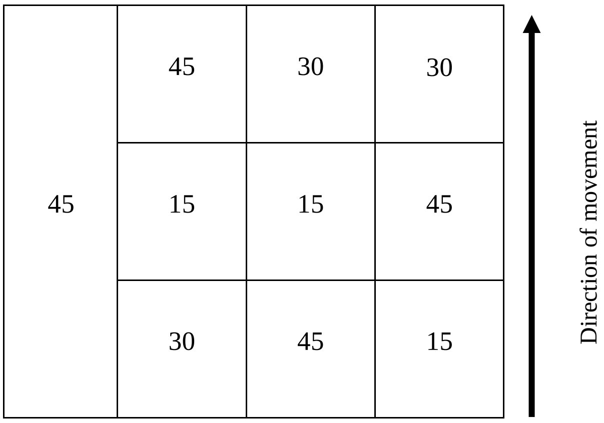
As stated in (Tahmasebi *et al.*, 2021), a vertical standard penetrometer of the Hand penetrometer Eijkelkamp model (using cone No.1 with a diameter of 1 cm and cone angle of 60 degrees) was applied to measure soil compaction. Vertical penetration resistance was measured up to a depth of 45 cm at 9 points (3 points at a distance of 10m) near the movement path of the system.

Table 1- Some soil characteristics such as moisture content and bulk density

Depth (cm)	0-15	15-30	30-45
Moisture content (%)	5.42	6.68	2.75
Bulk density (g cm^{-3})	1.55	1.63	1.59

The first test was the evaluation of the variable-depth system when the pneumatic sensor did not send a signal. In the conducted experiment, the depth control system sends a command to the tool to reach into identified depths (three depths of 15, 30, and 45 cm). For the experiments, three plots with a width of 3m and a length of 30m for three proposed depths according to Fig. 10 were selected as 3 repetitions. In this case, the amount of fuel consumption and the travel distance to reach the desired depth of the VDT tool was measured in three repetitions. The fuel consumption was determined in each treatment by measuring the volume of tractor fuel consumed. Firstly, the fuel tank of the tractor was filled full, and the subsoiling operation was performed. Then, the fuel tank was refilled, and the consumed fuel was measured via a graduated cylinder.

The VDT tool's performance when the depth control was OFF (as a common subsoiler) was compared with the VDT tool in terms of energy consumption in a plot with a width of 3m and a length of 90 m (Fig. 10). For this purpose, the VDT tool was worked with a constant depth of 45 cm (maximum). The T-test at the statistical level of 1% was utilized to compare the values of the fuel consumption in two subsoiling methods with variable and uniform depths.



45	45	30	30
	15	15	45
	30	45	15

Fig. 10. Evaluation map of VDT tool in the field

The second test was the performance of the variable-depth system while the pneumatic sensor determined the soil compaction, and sends a signal to control depth. The accuracy of operations with variable depth and commanding from the pneumatic sensor and the simultaneous validation of the operation were evaluated. Along the 90m path every 1m interval, the depth of penetration was measured and the profile of the path subsoiling was drawn. For validation of the profile, every 5 m (near the penetrometer point) all over the path the soil was dug up, and the tillage depth was measured by a ruler. Moreover, the fuel consumption along the path was measured by the full fuel tank method.

Results and Discussion

Static evaluation

Fig. 11 illustrates an example of determining the response time of the hydraulic circuit to the open-closed signal applied to the directional control valve. This curve demonstrates the variation in the angle of the depth control wheel from 90 to 60 degrees (30 degrees of rotation), which indicates the change in depth from zero to 30 cm. The horizontal axis of the diagram shows the number of samples per time, and according to the test response time, delay time and rise time were calculated. The values of response time, delay time, and rise time for different depth changes were achieved, and are listed in Table 2. The system accuracy or standard error percentage was computed from Equation (1) and the results are displayed in Table 1.

$$E\% = \frac{D_{\max imum} - D_{s\tan dard}}{D_{s\tan dard}} \times 100 \qquad (1)$$

Where $D_{\max imum}$ and $D_{s\tan dard}$ are the maximum depth measured in each repetition and desired depth, respectively.

It can be seen in Table 1 that the delay time is less through the opening of the hydraulic cylinder compared to closing because of the larger cross-section of the cylinder when is extending. When the setting depth is 0 to 15 cm, the response time is 18.22s.

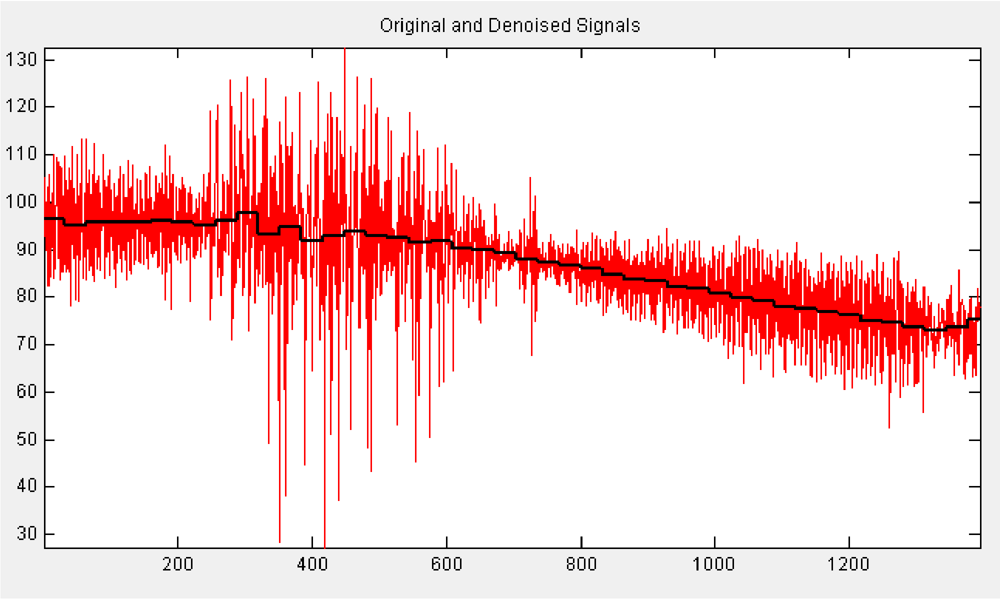


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Fig. 11. Diagram of the response of the hydraulic circuit to the open-closed signal applied to the directional control valve; a) The main recorded signal, b) The signal after the noise filtering by wavelet conversion

Table 2- Results of evaluation of VDT tool using a shaft encoder

Setting depth (cm)	**Response time (s)**	**Delay time (s)**	**Rise time (s)**	**Error (%)**
0 to 15	18.22	4.05	14.17	6.66
0 to 30	27.86	3.98	23.88	6.25
0 to 45	36.72	8.4	28.32	8.33
15 to 30	16.32	4.5	11.82	2.1
15 to 45	15.33	2.06	13.27	5.55
30 to 45	7.5	1.5	6	1.42
45 to 0	41.76	10.44	31.32	6.33
45 to 30	8	1.5	6.5	6.25
30 to 15	13.18	1.68	11.5	2.8
30 to 0	43.2	8.6	34.6	1.3
15 to 0	26.6	4.1	22.5	3.07

But the response time is 27.86s when the setting depth is 0 to 30cm. It is clear that although the desired depth has been doubled, the response is less than twice. That is because of the pressure behind the cylinder piston and the internal friction at the end of the opening path is reduced. In Table 2, a similar trend saw for the third setting depth (0 to 45 cm) that was although the depth has tripled; the response time is less than three times. In addition, by investigation of two other setting depths (15 to 30 cm and 30 to 45 cm), the response time of 30-45 cm depth was half of the 15-30 cm depth is shown that in extending the depth of 30-45 cm, internal friction and pressure are lower, so the resistance inertia is low. Furthermore, Table 2 proved that due to the higher resistance inertia, the error data of extending is higher than the error of closing the hydraulic cylinder

Field evaluation

The results of the VDT tool evaluation in the first stage, including the traveled distance of the tine to reach the desired depth and the amount of fuel consumption, are given in Table 3, respectively. The average values of the traveled distances to get the desired depths to indicate that the VDT tool can reach the anticipated depth in an appropriate time. The results of static and field evaluations were consistent with the results of Gohari (2006).

According to the results of static and field evaluations, enhancing the performance of the proposed VDT tool requires a hydraulic cylinder with higher extending and closing speeds to have a lower needed open/close time. Another solution for this issue is using a gearbox for gauge wheel axel to increase the speed of wheel deployment.

Table 3- Results of evaluation of VDT tool in the field through the first step

Repetition	Depth			Fuel consumption (L ha^{-1})
	15 cm	30 cm	45 cm	
	Traveled distance to reach the desired depth (m)			
1	0.9	1.6	2.2	67.71
2	1	1.7	2.15	64.40
3	0.9	1.55	2.1	68.19
Mean	0.93	1.62	2.15	66.76

The amount of fuel consumption in the three repetitions of the experiments was 67.71, 64.4, and 68.19 L ha^{-1}, respectively. When the depth control system was OFF, this value was obtained 80.8 L ha^{-1} at the maximum depth of 45 cm. As it is known, the fuel consumption in the variable-depth operation in comparison to the maximum depth in the three repetitions of the experiments had decreased by 16.2, 20.3, and 15.6%, respectively, and the average was 17.36%.

The results of the t-test analysis related to the fuel consumption values in two methods of subsoiling with variable depth and constant depth (as a control) at the statistical level of 1% are displayed in Table 4. The finding showed that the amount of fuel consumption reduction at the statistical level of 1% is significant. Furthermore, the comparison of the mean value of the two methods is given in Table 5.

Table 4- Results of T-test analysis

	Degrees of freedom	t	<p
Fuel consumption	4	-8.46	0.0005

Table 5- Results of comparing the mean amount of fuel consumption in two subsoiling methods with variable depth and uniform depth

Method	Mean of fuel consumption
Subsoiling methods with variable depth	66.76a
Subsoiling methods with uniform depth	80.80b

In fact, the findings of the research indicated that the amount of fuel consumption reduces when the VDT tool is used, which was consistent with other researchers' reports (Fulton *et al.*, 1996; Abbaspour-Gilandeh *et al.*, 2005; Alimardani *et al.*, 2007; Rapper *et al.*, 2007; Fox *et al.*, 2018; and Meselhy, 2021). However, the percentage of the reduction was lower than the results of their reports, which can be due to two reasons: 1) the pneumatic sensor (in front of the tractor) worked and pushed at the depth of 45 cm in all tests; 2) the soil of the field was highly compacted based on vertical standard penetrometer data (Tahmasebi *et al.*, 2021).

In the second phase, when the tool has been operated with variable-depth mode using pneumatic sensor signals, the pneumatic sensor tine penetrated well into the soil and sent the control command to the hydraulic cylinder continuously. The subsoiling profile by VDT is plotted and shown in Fig. 12. Based on the amount of field compaction (shown in the diagrams of Fig. 21-23 (Tahmasebi *et al.*, 2021)), and adjusting the pressure-sensitive switches on 1.2 bar, the tool was worked in the depth range of 30 to 48 cm through the whole test path. However, as clear in the figure, the compaction and the traveled distance by the tool to stabilize the depth were less in the first 10 m of the path. On the other hand, the actual depth of VDT which measured via ruler is depicted in Fig. 12. Comparison between the actual and working VDT depth was confirm that the VDT has been able to perform the subsoiling operation well.

The fuel consumption was measured along a path equaled to 73.7 L ha^{-1}. The rate of reduction of the fuel consumption compared to the control method (subsoiling at the constant depth of 45 cm) showed a decrease of 8.79 %. Although the fuel consumption was decreased during this test, due to the high soil compaction along the path and the operation of the tool at the high depth (45 cm), the fuel consumption was compared only in the first step of the evaluation with the control treatment.

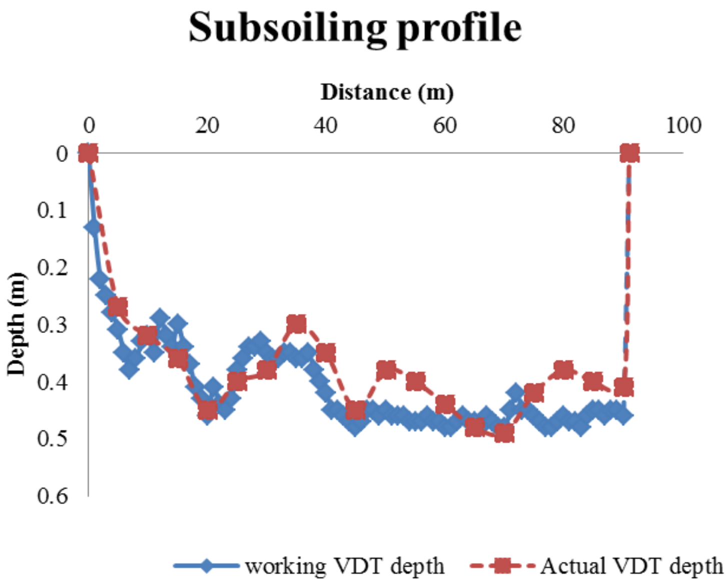

Fig. 12. The subsoiling profile

Conclusion

In this research, a variable-depth tillage (VDT) tool was developed which the working depth was controlled via a signal sent by a pneumatic sensor and evaluated by static and field methods. Through static evaluation, the system response time to reach 95% of the desired depths was measured. Field evaluation of the VDT tool was conducted in two steps. In the first step, the evaluation of the VDT tool was performed when the pneumatic sensor did not send a signal. The amount of fuel consumption and the travel distance to reach the desired depth of the VDT tool tine were measured in three repetitions. To compare the fuel consumption, the VDT tool was worked in the OFF depth control. During the second stage, the VDT tool was evaluated in variable depth using the signals sent by the pneumatic sensor. The mean values of the traveled distances to reach the desired depths indicate that the device can penetrate into the desired depth at a suitable time. The fuel consumption in the variable-depth technique decreased by an average of 17.36% compared to the test maximum depth, and indeed less fuel consumption in the variable-depth subsoiling was perceived. Through the second step of field evaluation, the sensor tine penetrated the soil perfectly and sent the control signal to the hydraulic cylinder continuously and the VDT tool worked at the depths sent by the sensor.

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توسعه و ارزیابی مزرعه‌ای یک خاک‌ورز عمق متغیر بر اساس اندازه‌گیری حسگر پنوماتیکی افقی

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چکیده

فشردگی خاک می‌تواند به‌طور طبیعی اتفاق بیفتد یا ناشی از رفت و آمد ماشین‌ها باشد. عملیات زیرشکنی اغلب برای سست کردن لایه تراکم خاک و کاهش مقاومت خاک تا سطوحی که امکان رشد و نمو ریشه را فراهم کند، استفاده می‌شود. عملیات زیرشکنی با عمق متغیر به‌طوری‌که خواص فیزیکی خاک را تنها در مواردی که خاک‌ورزی برای رشد محصول مورد نیاز است اصلاح می‌کند، پتانسیل کاهش نیروی کار، هزینه‌ها، سوخت و انرژی مورد نیاز را دارد. از آنجایی که این مطالعه با هدف انجام عملیات زیرشکنی با عمق متغیر انجام شد، ابزار خاک‌ورزی با عمق متغیر (VDT) طراحی و ساخته شد. یک حسگر پنوماتیکی مجهز به چند نازل برای پیش‌بینی همزمان عمق لایه متراکم خاک در سه عمق (۱۵، ۳۰ و ۴۵ سانتی‌متر) و ارسال سیگنال برای کنترل عمق خاک‌ورز VDT استفاده شده است. ارزیابی سامانه ابزار VDT به دو روش استاتیکی و دینامیکی انجام شد. در ارزیابی استاتیکی، زمان پاسخ سیستم برای رسیدن به ۹۵ درصد عمق‌های موردنظر اندازه‌گیری شد. ارزیابی دینامیکی زیرشکن نیز در دو مرحله انجام شد. میزان مصرف سوخت و مسافت رسیدن تیغه‌های زیرشکن به عمق موردنظر در سه تکرار اندازه‌گیری شد و با دستگاه زیرشکن (در حالت کنترل عمق خاموش) مقایسه گردید. میانگین مصرف سوخت در حالت عمق متغیر نسبت به عمق بیشینه ثابت به میزان ۱۷/۳۶ درصد کاهش پیدا کرد. همچنین سنجنده به‌خوبی وارد خاک شده و فرمان کنترل را به سیلندر هیدرولیکی به‌طور پیوسته ارسال می‌کرد و دستگاه زیرشکن، خاک را در عمق‌های ارسالی از سوی سنجنده زیرشکنی نمود.

واژه‌های کلیدی: خاک‌ورزی دقیق، خاک‌ورز عمق متغیر (VDT)، حسگر پنوماتیکی، کاهش مصرف سوخت، لایه خاک متراکم

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