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Design, Control and Prototype Implementation of Maintenance Machine for Trenches

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Abstract: *Trenches have a special importance in construction operations as they are widely used in both civil and military engineering. However, maintaining dozens kilometers of trenches that are located in an area of harsh weather condition can be difficult to be achieved manually. In this paper, the design and control of a new remotely controlled Trenches' Maintenance Machine (TMM) is presented. Elements like achieving machine stability and maneuverability, providing high performance while delivering the necessary traction in loose sand or mud, and using a powerful pneumatic system to overcome earth cutting resistance have been considered during the design procedures. A scaled prototype of the machine has been implemented and tested using an indoor soil-bin facility. The satisfying results assure the good functionality of the machine sub-systems as well as the reliability of the machine to accomplish the task successfully and within the required standards.*

Keywords: *Mobile robot control, Scaled prototypes, Soil-machine systems, Terramechanics.*

I. INTRODUCTION

Soil-machine systems refer to systems in which the soil and machine tools interact to accomplish a specific task or purpose of production. These systems can perform many tasks such as tillage in agriculture, earth moving in civil engineering, and trench forming for installing long distant fuel pipelines and military fortifications.

A trench can be defined as a type of excavation whose depth is deeper than its width. Trenches have a special importance in construction operations as they are widely used to place underground easily damaged and obstructive infrastructure or utilities such as fuel and gas pipelines, electric cables, and sewage. Also, they are used as search trenches which are important to search for pipes and other infrastructures that are known to be underground, but whose exact location has been lost. Finally, trenches are used for transport purposes such as installing depressed motorways, open railway cuttings, or canals. On the other hand, in military engineering trenches and ditches are effectively used to shelter troops and firearms. They can extend for kilometers along a front without interruption. Some types of trenches and ditches can be up to 100 cm wide and 190 cm deep. While maintenance and repair operations are frequently needed to keep good state of the infrastructure of trenches, custom made machines are needed to apply any maintenance or repair requirements to such infrastructures [1].

The problem here can be defined in making a maintenance machine for ditches and utility trenches of width up to 100 cm especially those prepared for laying pipelines through long distances. This type of trenches and ditches is normally prepared for laying gas and petroleum pipelines through distant areas which are mostly deserts whose climate may backfill many parts of these trenches. The key point of this paper is to present the design and control of a new remotely controlled machine used for trenches' maintenance.

II. DESIGN OF THE TRENCHES' MAINTENANCE MACHINE AND ITS CONSTRUCTION

The design of a soil-system machinery include many factors that is related to required power, weight of the machine, spatial location of center of gravity, width and contact length of track, initial track belt tension, effective tractive effort, diameter of front idler and rear sprocket, number of road rollers, and suspension apparatus. In this paper, we focus on presenting the basic ideas of the sub-systems of the trenches' maintenance machine (TMM).

There are many detailed methods for engineering design process that can be used to devise a system to meet a desired need. Most of them have some common elements, such as brain-storming, analysis, and iterative decision making. In this paper, steps of the engineering design process from [2] are used. Elements such as recognition of need followed directly by problem definition with the idea based on components of the design have been accomplished. Before a system can be analyzed, it must at least be conceptualized. Therefore, synthesis must occur first and an initial concept to solve the problem is then determined. Once a concept is approved, schematics and layouts are created to visually depict the concept to other groups of people. Eventually, this will lead to detailed design and detailed drawings of each component along with assembly drawings. The maintenance machine consists of a tractor unit, a control unit, a sand disposal system and a blade attached to the front of the tractor unit as shown in Fig.(1). The tractor unit is a rectangular steel deck that carries the motors, the sand disposal system, the attachment and the controls. The control unit is responsible for enabling the operator to control the machine during all phases of operation.

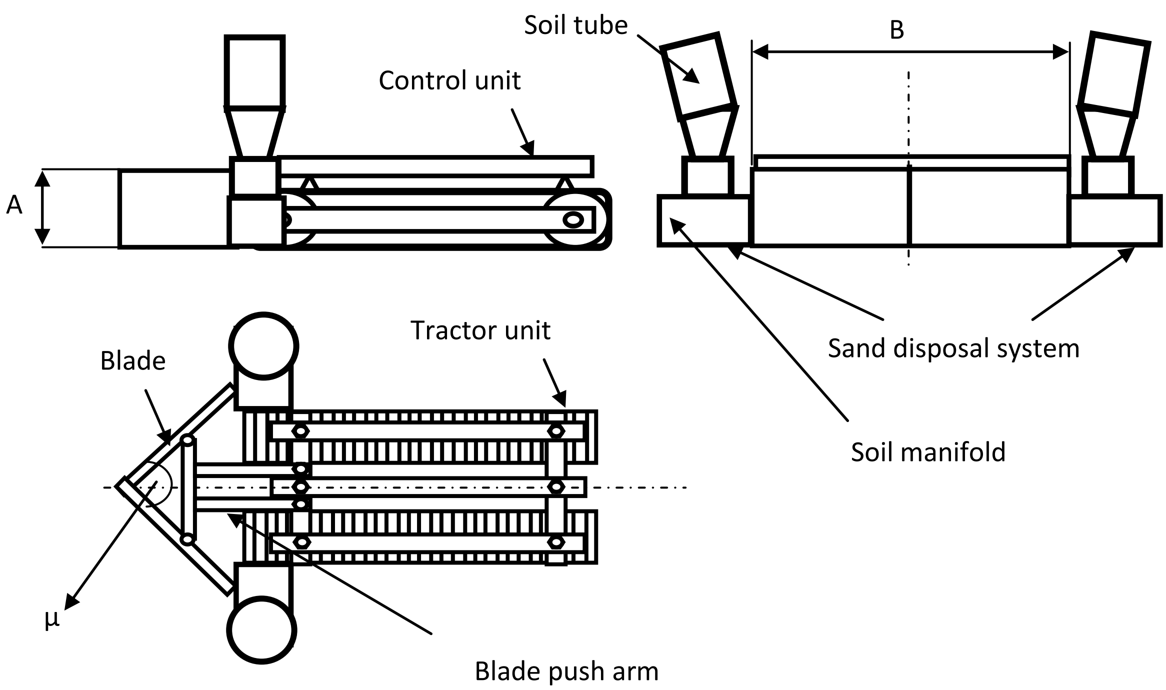

Fig. (1): An assembly drawing for the trenches maintenance machine (TMM).

2.1 The Blade

The blade specific parameters, shown in Fig. (1), are the blade angle (μ), the blade vertical height (A), blade width (B) that is the distance between both blade sides, and the maximum cutting depth (D) that is the maximum vertical distance that the center of the cutting edge can be lowered below ground with no blade tilt or angle.

The blade is used to shear, cut, and push or roll material ahead of the tractor. The blade consists of two 45^o angled curvatured moldboards welded in the arrow-head shape with replaceable bolted teeth (cutting edges). In contrary to the design of the "U" shape blade used in some types of dozers, the arrow-head shape design of the blade assure cutting of earth and then rolling quantities of soil asides with fixed rate (as the machine's operation speed is kept constant) where they are collected in soil manifolds. The soil is then plowed outside the trench through soil tubes using the effect of the air generated by the blowers that are located directly behind the soil manifolds.

The design of the machine allows the blade to be raised or lowered in the vertical plane of the blade. A simple pneumatic system is used to control the cutting depth of the blade using a tilting pneumatic cylinder that is connected to the blade push arm, which is used to connect the blade to the tractor. The blade teeth cut the earth at the beginning of the operation phase and play a major role in how the machine performs. The hardened-steel cutting edges are bolted to the back of the moldboards which allows for their easy replacement as they receive most of the abrasion and therefore wear out rapidly. To keep a simple design of the machine, the blade can neither be pitched forward or backward (pitch angled) nor the mounted blades can be turned from the direction of travel as varying the angle of attack of the cutting edge is not needed to accomplish trenches' maintenance tasks. Former soil-machine system studies [3,4,5] provide us with the blade specific parametrs convineint to work in gravelly sand such that (B/A) ratio was chosen to be 3, blade angle (μ) is chosen to be 80^o, and the moldboard angle of curvature (θ) is chosen to be 45^o.

2.2. The Tractor

The tractor consists of two main units, the power unit and the running gear unit. The power unit includes four DC motors that are used to independently drive the right sprocket, the left sprocket, the cutting depth pneumatic system, and the blowers of the sand disposal system. The running gear unit design assures the transform of the applied torque to the driving sprockets during the translatory motion of the equipment. It includes undercarriage, suspensions, and propeller. Generally in crawler machines, the steering is carried out by changing the relative velocities of the supporting tracks. As the relative velocity increases, the turning radius decreases and vice verse. This is called "skid steering" or "differential steering". The machine steering mechanism is designed to be skid steering which has the advantages of simple control along with its suitability for off road operation. The steering mechanism main idea depends on establishing a speed difference between the left and right motors used for the machine driving.

The undercarriage is a frame that supports all sub-systems of the machine. The track assembly consists of a continuous chain surrounding the track frame and drive sprockets. The links of the chain provide a flat surface for the track rollers to pass over, as they support the machine. Track shoes are bolted to the outside links of the chain and distribute the weight of the machine over a large surface area as shown in Fig. (2).

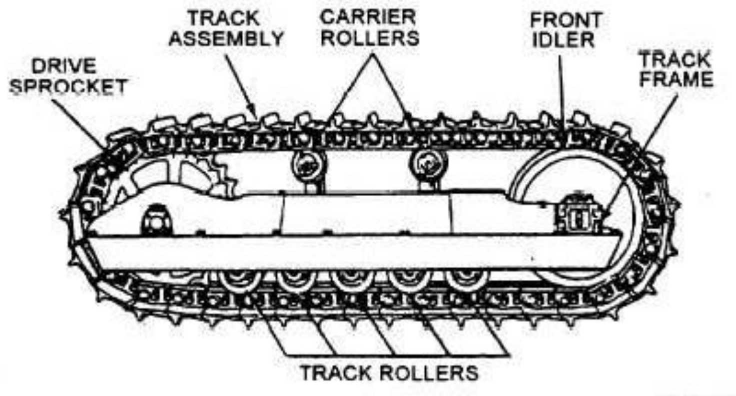

Fig. (2): Track assembly.

Track's low center of gravity and relatively large footprint increase stability of the machine during operation and provide smooth working pattern over rugged terrain. Also, track dimensions and design minimize the potential for trench collapse in loose soil conditions.

2.3. The Pneumatic System

The pneumatic circuit main task is to control the pneumatic cylinder which is responsible for giving the blade a specific cutting depth and to keep this cutting depth during the operation. The main advantages of the pneumatic system can be summarized in the small size and high actuating force, high power to weight ratio, high efficiency, easy to control, flexibility, low friction losses with a minimum possibility of leakage as the machine main job of maintenance of trenches acquires low pressure pneumatic circuit [6]. The main components that constitute the pneumatic circuit are the pneumatic storage and preparation unit, a compressor operated by a DC motor, a safety valve, a control valve, a cooling-filtering-drying integrated unit, pneumatic cylinder, and hoses. Figure (3) represents a typical pneumatic control system used for blade cutting depth control.

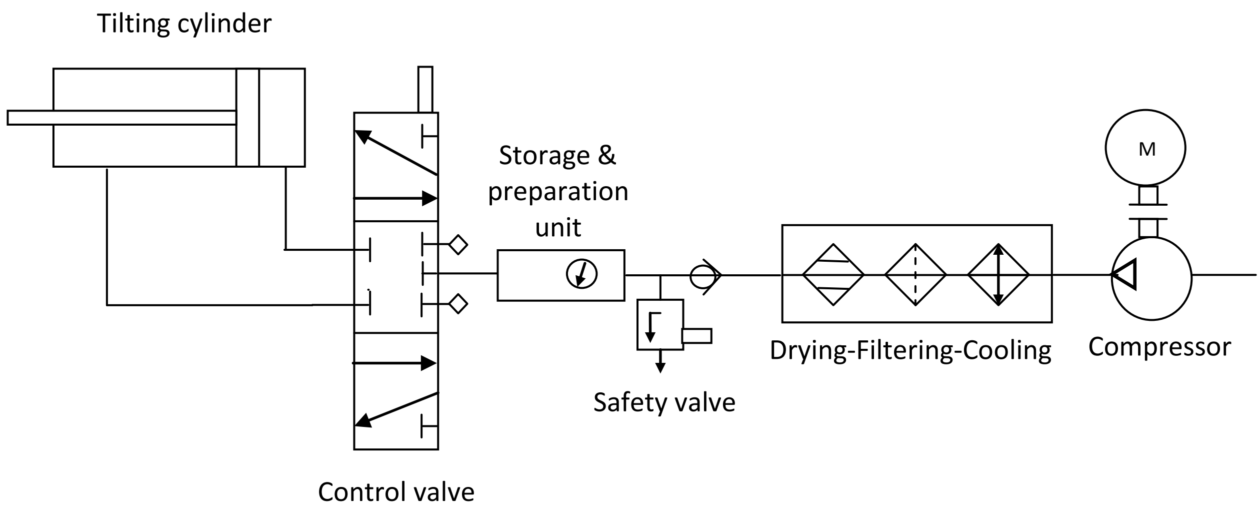

Fig. (3): Pneumatic circuit.

The pneumatic reservoir is attached to the rear of the machine to serve as counterbalance that increases the traction forces during operation. As the cutting depth should be kept constant, the cylinder is manually operated through the control valve at the beginning of the operation stroke. The positions of the control valve serve the different regimes of operation of the machine. The first position of the control valve is responsible for lowering the blade to reach a specific cutting depth while the machine is stationery. The second position of the control valve is engaged during the machine operation where the cutting depth is required to be maintained by the cylinder. Finally, the third position is responsible for raising the blade off the ground.

2.4. Sand Disposal System

The idea of sand disposing in our machine is similar to the disposing of waste in some mechanical equipment such as branches shredding machine [7]. The branch trimming process may generate waste in the form of dust, debris or wood where cleaning is completed at the job site, waste will often be left at the cleaning site (dust, grinded wood, and debris are blown from the machine using compressed air). This application depends mainly on the assumption that the loose sand-air mixture can be considered as a high density continuum fluid.

The main advantage of the design is that it allows the machine to drift large volume of sand efficiently over long distances. During operation, the center section of the moldboards drifts the soil with aside roll. The 45^o angled curvatured moldboards assure rolling materials outward to keep the soil moved toward the soil manifolds at both sides of the blade with a minimum loss. The power train of the machine is shown in Fig. (4).

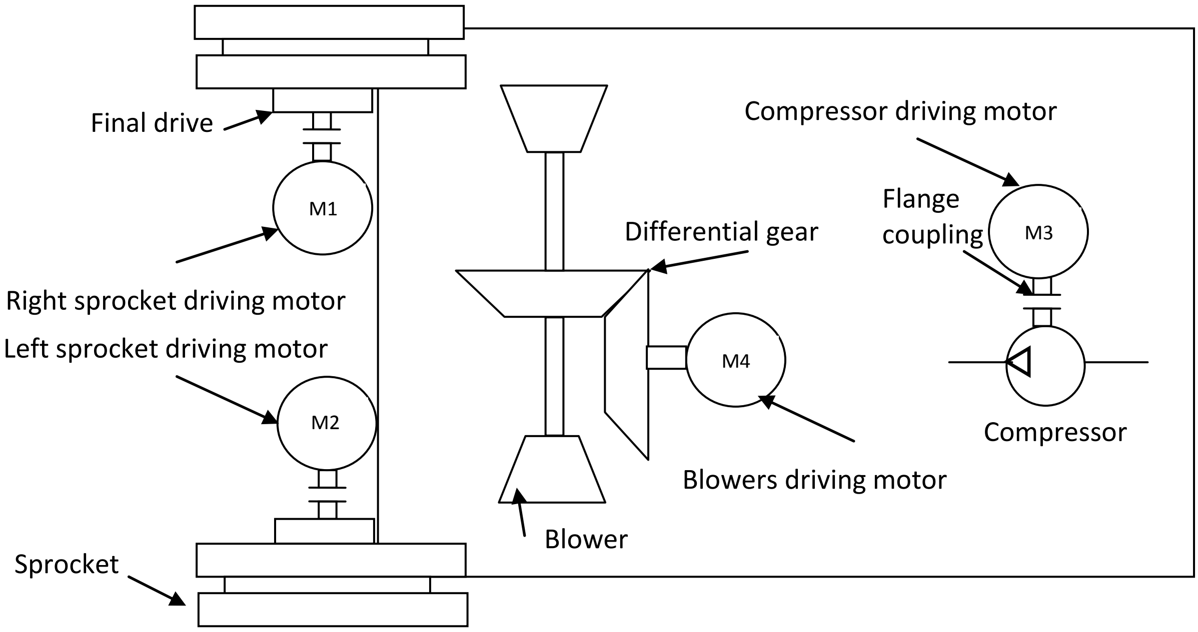

Fig. (4): Power train of the trenches maintenance machine (TMM).

III. POWER CALCULATIONS

From the machine construction explained in the previous section, it can be concluded that the system required total power can be defined as the sum of powers needed to drive each system of the machine taking the friction and losses waste in each system into consideration; such that:

$$P_t = P_p + P_d + P_b \quad (1)$$

Where Pt is the total power needed by the machine, P_p is the power needed to operate the compressor responsible for actuating the pneumatic cylinder which cuts the earth at the beginning of the operation. P_d is the total power needed to drive the machine that can be subdivided into two parts; the machine steering part P_s for skid steering system, which is small compared to the other major part; the earth cutting part P_c that is the power needed to drive the machine while overcoming the earth cutting resistance. P_b is the power required to operate the blowers. Also a small part of the total needed power should be dedicated to actuate the controls and the control unit. Since the machine main task is to exert a load on the blade during penetrating the earth to maintain the blade the required cutting depth, then it is expected that the main power needed to drive the machine comes from the calculations of the cutting forces exerted by the blade to overcome the earth resistance during the operation as will be explained in the following subsections.

3.1 Pneumatic Circuit Power (P_p) Calculations

The pneumatic circuit power P_p is the power required to overcome the soil resistance exerted on the blade during penetration the earth at the beginning of the operation to give the blade the required cutting depth. Considering soil-machine systems, good tool performance leads to considerable saving in energy and labor as well as improvement in working efficiency in the daily operations concerning earth cutting. Soil-machine systems studies can be dated back to early 1900s, but the real breakthrough has been achieved in the last three decades. Many investigations have been conducted using either an empirical or analytical approach, however because the complexity in soil mechanical behavior, empirical results are hardly extended to a general case. In this paper, we adopt the analytical approach where soil in front of the blade is broken up into several parts, each of which is considered as a rigid object. The limit equilibrium method is applied here to analyze the force balance in the entire system. When a single tooth of length (a_1) and width (b) is used for cutting the earth at a rake angle (α) and single tooth cutting depth (d) which will equals to ($a_1.\sin\alpha$), a set of resistance forces will be acting on the tooth. To determine these forces the soil shear wedge, shown in Fig. (5), should be studied [8] where:

m_1…. Weight of soil wedge being cut under the ground.
W …. Normal force from effects above the surface.
F_{f1} …. Friction force between soil and shank surface.
F_{a1} …. Adhesion force between soil and shank surface.
F_{sf} …. Friction force on the side of the soil wedge.
F_{sc} … Cohesion force on the side of the soil wedge.
F_{rf} …. Friction force between soil wedge and ground at the rupture surface.
F_{rc} …. Cohesion force between soil wedge and ground at the rupture surface.

Q …. Normal force on the rupture surface.
δ ….. The angle of soil metal friction
ϕ ….. Soil internal friction angle
β …. Angle of rupture plane with the X axis
μ …. Blade angle (angling)
θ …. Blade angle of curvature

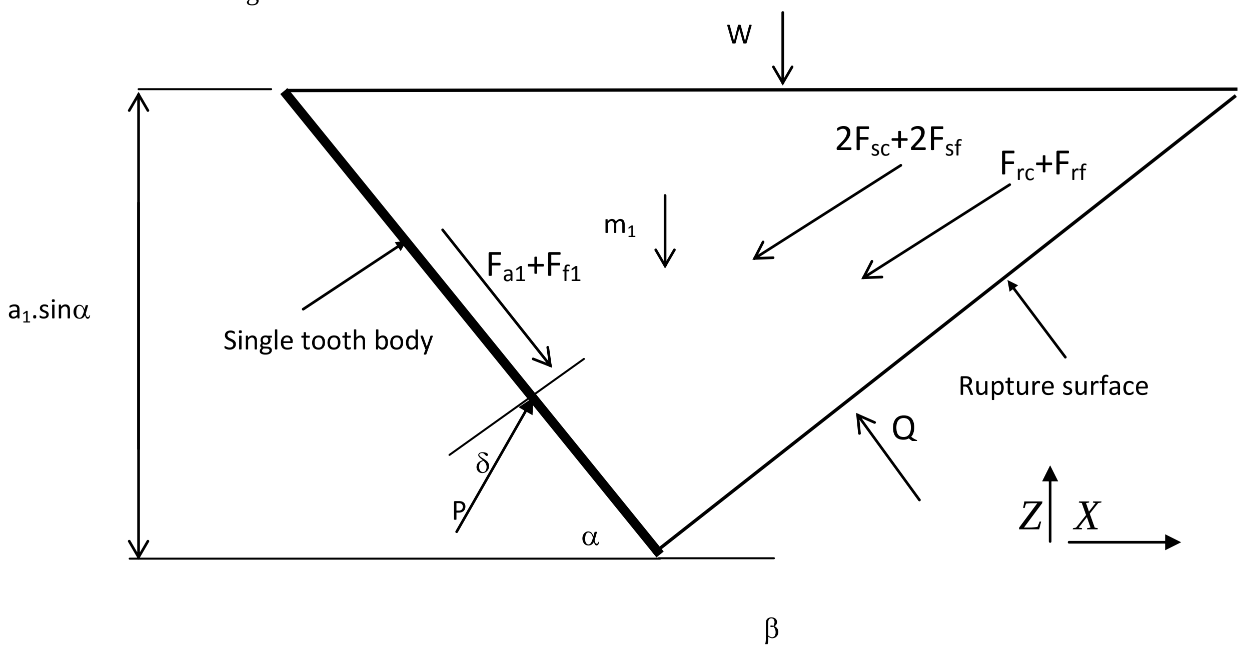

Fig. (5): Force analysis under the earth due to earth cutting by a single tooth

Studying the wedge as a free body diagram [8], it is noted that F_{sc} and F_{sf} are multiplied by two due to its generation from the two sides, it can be derived that:

$$P_x = Q.\sin\beta + (2.F_{sc} + 2.F_{sf} + F_{rf} + F_{rc})\cos\beta - (F_{a1} + F_{f1}).\cos\alpha \quad (2)$$

$$P_z = -Q.\cos\beta + (2.F_{sc} + 2.F_{sf} + F_{rf} + F_{rc})\sin\beta + (F_{a1} + F_{f1}).\sin\alpha + W + m_1 \quad (3)$$

but, $P_x = P_p.\sin(\alpha+\delta)$ and $P_z = P_p.\cos(\alpha+\delta)$ (4)

Therefore, P_p can be derived for unit linear velocity of the rod of pneumatic cylinder in the following form:

$$P_p = \frac{(2F_{sc} + 2F_{sf} + F_{rc})\cos\phi - (F_{a1} + F_{f1})\cos(\alpha+\beta+\phi) + (W + m_1)\sin(\phi+\beta)}{\sin(\alpha+\delta+\phi+\beta)} \quad (5)$$

3.2. Traction Power (P_d) Calculations

In the previous subsection the power needed to actuate the pneumatic cylinder during the whole operation regime to overcome the earth cutting resistance has been calculated. Considering that the machine is designed to accomplish only maintenance jobs for trenches and not building new ones, therefore it is safe to assume dealing with rather low soil cohesion forces, low soil-tool adhesion forces, and low cutting depths which means that the flat teeth, rather than the blade curved portion, are responsible for cutting the earth until reaching the cutting depth. Now the total earth resistance forces exerted on the blade calculated in [3-5,8] can be used to estimate the power needed for traction which is essential to design the track assembly through the empirical formulas included in [8]. The free body diagram of the blade during operation, shown in Fig. (6), illustrates that the (X,Z) reference axes are taken according to the blade such that the X axis is taken in the direction of movement of the blade which makes an angle equals to (μ/2) with the blade where (μ) is the blade angle. As a result of the side movement of the slice on the blades to the sides, friction and adhesion forces are generated and their direction will be aligned with the blades as shown in Fig.(6). Therefore, it can be concluded that:

$$F_{Xm} = P_x + 2F_{bx}.\sin(\mu/2) + 2(F_{fy} + F_{ay}).\cos(\mu/2) \quad (6)$$

$$F_{Zm} = P_z + 2F_{bz} \quad (7)$$

where:

F_{Xm} .... the total draft resistance forces exerted on the blade.
F_{Zm} the total vertical resistance forces exerted on the blade.
F_{fy} …….soil-blade friction force that affect the curved portion of the blade.
F_{ay} …….soil-blade adhesion force that affect the curved portion of the blade.
F_b ……..soil pile weight force that affect the curved portion of the blade.

Neglecting the soil adhesion and friction forces and assuming low cutting depth and therefore a small soil pile in front of the blade, it can be derived that total draft and vertical forces on the blade are:

$$F_{Xm} \approx P_x \text{ and } F_{Zm} \approx P_z \quad (8)$$

This means that the required traction power (P_d), for a unit linear velocity of the machine, is approximately equal to the power required by pneumatic system for unit linear velocity of the rod of pneumatic cylinder.

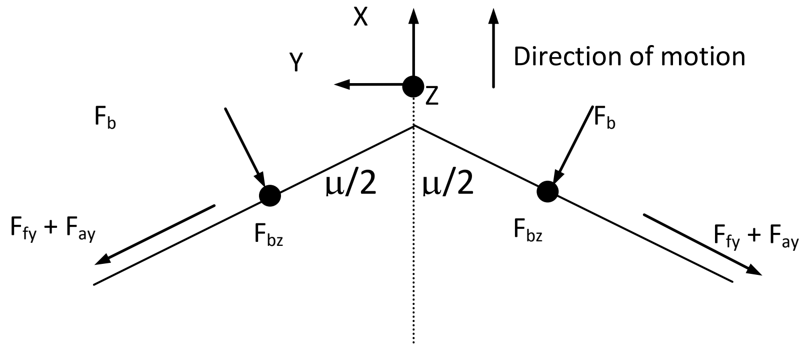

Fig. (6): Draft and vertical forces acting on the blade.

3.3 Sand Disposal System Power (P_b) Calculations

The total power needed to drive the two blowers can be calculated from the energy calculations which is subdivided into the kinetic energy (K) and the potential energy (H).
The kinetic energy can be derived from the equation

$$K=0.5mv^2 \quad (9)$$

Where:
m… The weight of the air-sand mixture flow
v... The air-sand mixture flow speed at a point on a streamline,
α … The rake angle
D… The blade cutting depth
B… The blade cutting width

The flat part submerged in the soil and whose vertical projection equals (D), as shown in Fig.(7), is divided into two portions. The tooth portion of length a_1, and another portion of the blade whose length equals ($D/\sin\alpha - a_1$). The amount of soil cut per one meter travel accumulating to form a prism can be calculated as:

$$Q_s = B.\sin(\mu/2).(D - a_1\sin\alpha) \quad (10)$$

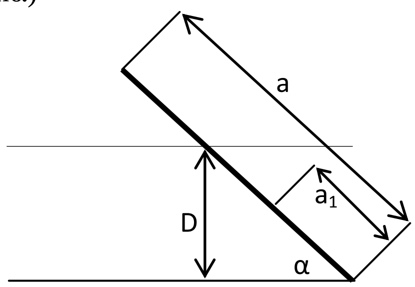

Fig. (7): The submerged part of the blade in earth.

The potential energy can be calculated assuming that loose sand-air mixture can be considered as a high density continuum fluid. Therefore, Bernoulli's principle from fluid dynamics can be used to derive a common approach in terms of total head or energy head H as follows:

$$H = (v^2 / 2g) + h = (v^2 / 2g) + (p/ \rho g) + z \quad (11)$$

where:
v... The fluid flow speed at a point on a streamline,
g ... The acceleration due to gravity,
z ... The elevation (head) of the point above a reference plane
p... The pressure at the chosen point, and
ρ... The density of the sand-air mixture at all points.
h ... the pneumatic head which is the sum of the elevation z and the pressure head

Therefore, the power of motor needed to drive the two blowers (P_b) as a part of the overall power can be calculated for unit operating velocity of the machine.

IV. MACHINE CONTROL

Most of the used infrastructure maintenance machines are wire-based systems. The primary purpose of using the wires is to facilitate data communication and powering of motors and sensors. However, wire-based systems are practically difficult to use especially for a structure of complex design. Wireless monitoring systems, to a great extent, offers a solution for such problem. Being modular in nature, wireless systems has better maneuverability in a way that they can be moved easily to new locations as needed. The availability of low-powered cheap microcontrollers and DSP chips, radio frequency (RF) integrated circuits, and the development of new wireless standards are all advantages that favor the use of such systems. Although wireless technology is one of the promising technologies of the future, less active researches have been done in the use of wireless controlled systems for infrastructural and environmental monitoring and repair [9]. In this section, we discuss the proposed design of the machine wireless control system. Although commercial off-the-shelf (COTS) wireless systems [10] can be considered, most of them have limitations that made us to develop our own wireless control system. The proposed control system consists of a base station and a motor control unit, signal and power conditioning hardware, microcontroller, RF transmitter and RF receiver. The system is powered by four C-cell alkaline batteries. The sensing units were connected to the base station outside the trench. The complex design of the trench ruled out the possibility of using other existing technologies like laser-based controlled systems.

The Controlled vehicle works in ground conditions similar to that of tracked vehicles that use the skid steering mechanism. The skid steering depends on two different motors on each side of the vehicle. The required manoeuvre is achieved by the speed difference between the left and right motors of the vehicle. In our machine, it is preferable to control the motion of the vehicle wirelessly. The idea of sand disposing used in the TMM is based on blowing up the loose sand-air mixture using two blowers that are derived by a DC motor. The control of this DC motor is simply on-off control with maximum speed. Wireless control should be used in this case also. The designed easy-to-use control unit offers less jerking motions of the machine during operation. It allows the operator to steer the machine and adjust the cutting depth easily with minimum physical effort.

V. PROTOTYPE IMPLEMENTATION

Scaled prototypes are employed in many different areas of engineering to predict system performance under varying parameters on a relatively inexpensive scale. Scale model studies are based on the concept of similarity between the prototype and the real system, with the same physical laws governing both systems. Two systems will exhibit similar behavior if geometric, kinematic, and dynamic similarities are achieved. Although obtaining geometric similarity is a relatively simple matter, dynamic similarity requires that the ratios of all forces affecting the system must be the same [11].

The implemented prototype presented in this paper is a one-to-four scaled model of the real machine. The Rover 5® tracked robot chassis with settable ground clearance is used as the substructure of the TMM prototype to be controlled. Unlike conventional tracked chassis, the ground clearance can be adjusted by rotating the gearboxes in 5-degree increments. Stretchy rubber treads maintain tension as the clearance is changed. The standard chassis comes with two DC motors and gearboxes. Each gearbox, of 86.8:1 ratio, has an optical quadrature encoder with a resolution of 333.33 state changes per revolution [12]. The motor rated voltage is 7.2V and the TMM prototype speed is 1Km/hr. The TMM prototype is designed to allow Arduino development boards, power supply, and motor drivers to mount easily on the chassis [13]. The Rover 5 chassis with Arduino and motor driver unit mounted is shown in Fig. (8)

A four-channel motor driver unit designed originally for the Rover 5® chassis is used as shown in Fig.(8). Current sensing for each motor allows the processor to determine if a motor has stalled or is under excessive load. In the case studied, the motor control unit is connected to the front left and right motors of the TMM prototype as in two wheel drives, the DC motor that drives the compressor responsible for actuating the pneumatic cylinder, and the DC motor that drives the blowers.

The Arduino microcontroller is an easy to use and powerful single board computer that has gained considerable traction in the hobby and professional market. The Arduino is open-source, which means hardware is reasonably priced and development software is available. With the Arduino board, you can write programs and create interface circuits to read switches and other sensors, and to control motors and lights with very little energy consumption [14,15]. In the case studied, Arduino microcontroller is used to control the motion of the TMM prototype and the DC motor of the compressor, and the DC motor of the blowers. The control action is achieved using wireless network based on XBee. The Arduino is connected to the motor driver unit and the Rover 5® chassis as shown in Fig.(8).

The XBee radio frequency (RF) modem from Digi International® is a wireless transceiver. The XBee uses a fully implemented protocol for data communications that provides features needed for robust network communications in a wireless sensor network (WSN). Features such as addressing, acknowledgements and retries help to ensure safe delivery of data to the intended node. The XBee also has additional features beyond data communications for use in monitoring and control of remote devices [16]. A wireless network has to be formed using XBees. One XBee is updated with the "ZNet 2.5 Router®" firmware plugged into the XBee Shield on top of an arduino and the other XBee updated to the "ZNet 2.5 Coordinator" firmware and connected to the FT232 breakout which is plugged into the computer. The arduino should be connected to a power source so the wireless network is ready for transmission and reception, Fig.(9) shows the XBee plugged into the XBee shield on the top of Arduino as receiver and also shows the XBee connected to the FT232 breakout and plugged into the computer as transmitter.

The open loop control action is achieved using a personal computer (PC) as the base station. It controls the direction of the TMM prototype forward or backward and the speed of the left and right motors separately. The speed of each motor is controlled using pulse width modulation (PWM) technique through the motor driver unit. The control commands are sent from the base station to the vehicle using the wireless network implemented by XBees. The base station controls the on-off action of the DC motor of the blowers used for sand disposing and the DC motor of the compressor that actuates the pneumatic cylinder. The power supply unit provide the required power for the arduino and the receiver XBee attached to it via the shield. It also provides the motor driver unit with the necessary power for the motors. The transmitter XBee connected to the PC consumes its necessary power from the PC itself via a USB cable.

The pneumatic system of the TMM prototype has been calibrated and tested, as shown in Fig (10). It is worth noted that the TMM prototype has been tested under normal operating conditions using an indoor soil-bin facility, as shown in Fig. (11). The satisfying results assured the good functionality of the machine sub-systems and therefore the reliability of the machine to accomplish the required tasks successfully and within the required standards.

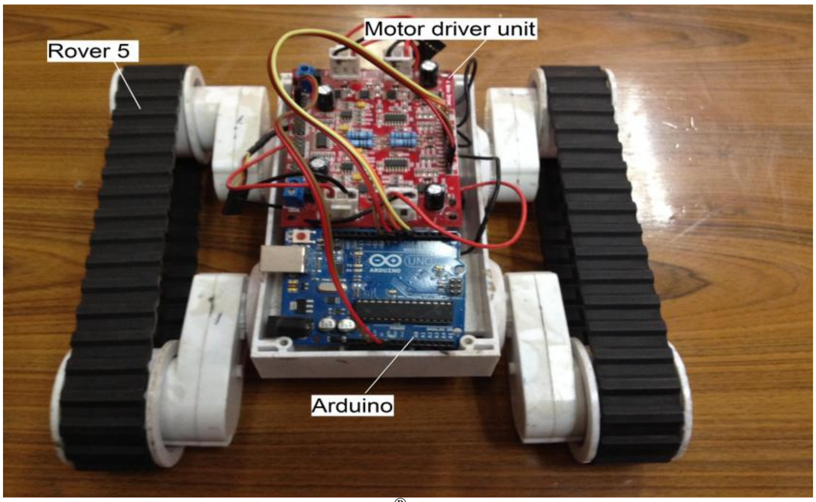

Fig.(8): The Rover 5® tracked robot chassis.

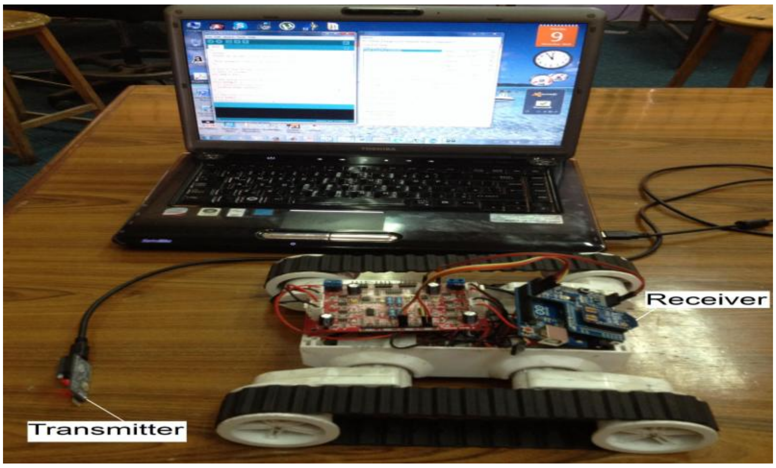

Fig. (9): Wireless connection between base station and the TMM prototype.

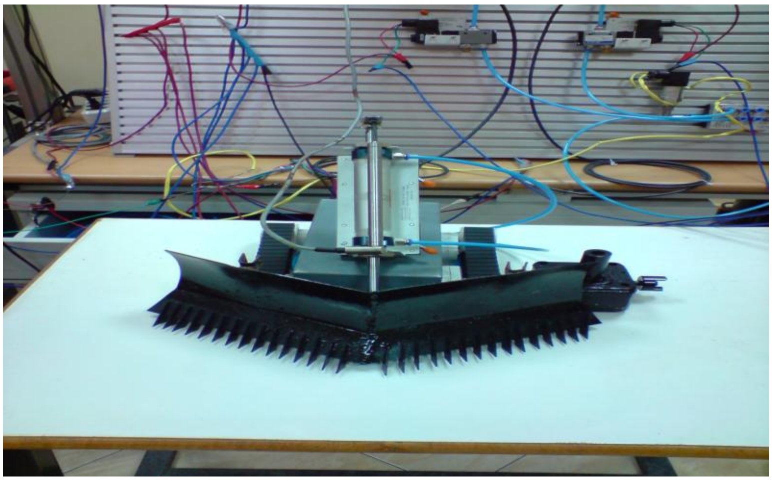
Fig. (10): Calibration and testing of the machine prototype pneumatic circuit.

Fig. (11): Testing the Prototype in an indoor soil-bin facility.

VI. CONCLUSIONS

This paper presents the design and control of a new remotely controlled machine used for trenches' maintenance (TMM). The machine is designed to meet the demanding conditions that trenches maintenance projects impose. The pneumatic system on the machine delivers the necessary power to overcome the soil cutting resistance. The designed easy-to-use control unit offers less jerking motions of the machine during operation. It allows the operator to steer the machine with one hand while adjusting cutting depth with the other in a way that helps in accomplishing the task with virtually no physical effort. Its compact design and easy to use control unit make our machine ideal for trenches' maintenance tasks especially for long distances. Although satisfactorily results are obtained when testing the scaled prototype of the machine in normal operational conditions to ensure reliability, more extra-tough tests should be performed in the future for harsh service conditions.

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