Designing of CNC Based Agricultural Robot with a Novel Tomato Harvesting Continuum Manipulator Tool

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Abstract— **The agriculture industry plays an important role in the needs of humankind. The rising of the world population, as well as the decrease in the number of workers in the agricultural sector, calls for an increased demand for food suppliers. In this paper, we propose a novel agricultural robot based on CNC machine namely FaRo (FArming RObot), for farming crops autonomously without any human intervention. What differentiates the FaRo from other farming platforms is the ability to carrying out the farming process from seeding to the harvesting of crops. Moreover, FaRo harvesting tool will be explained and demonstrated.**

Index Terms— **CNC machine, continuum manipulator, (“FaRo”), harvesting, autonomous**

I. Introduction

The agriculture sector is crucial for the basic needs of mankind due to food quantity directly affecting the sustainability of society. In recent years, the number of agricultural workers has been decreasing. According to the statistics of the World Bank, the number of agricultural workers in Japan has been declining from 2010 to 2017 as seen in Table 1 [1]. Moreover, the agriculture sector is not seen as an attractive field among the youth as well. From these circumstances, a shortage of labour has been a very recent concern. An alternative solution to resolving this decrease of a labour shortage is by applying automation technologies in the agriculture sector [2]. For instance, during the industrial revolution, the creation of agriculture machines such as tractors and cultivators reduced the potentially detrimental effects during the periods of labour shortages. In Japan, there have been many robotics and automation projects ranging from autonomous tractors, grafting robots, autonomous spraying mobile robots, seedling transplanter and vegetable harvesting machines [2]

Many prototypes of farming robotic system already exist such as autonomous tomato harvesting robotic system designed by Ooi and team, which has the feature to monitor a plot of land and gives real-time feedback information about soil, moisture and temperature status.

The Farmer Bot system provides information via the internet, as well, which makes the system remotely and flexible. An autonomous robot named Agro-Bot designed by Manoj has an autonomous seeding and watering system mounted on the robot. In India, about 70 per cent of people depend on agriculture for sustainable living, so the Agro-Bot was an alternative solution to this problem. With the addition of a solar panel, the Agro-Bot presents itself as a self-sustainable solution for off-the-grid farming [4].

Another issue an agricultural robot has to deal with is working within limited spaces which prove to be very challenging, due to leaves, sticks and other obstacles preventing conventional robot solutions. Similar research has been conducted by Yael Edan and his team while developing a melon harvesting robot mounted on a mobile platform. The robot consists of a Cartesian manipulator and mobile platform pulled by a tractor. The robot determines the melon by using image processing, does planning path to reach to the melon, then grasps the fruit gently to avoid damage to the fruit [5].

The harvesting process is a very work heavy and time-consuming process which scientists have been investigating for over five decades. Arguenon and his team developed Multi-agent based prototyping of agriculture robot for the harvesting of grapes in vineyards. The main features of the robot were detecting grapes, grasping them, harvesting and finally transporting the grapes. Many agricultural systems have been explained in the references for the automation of various harvesting processes [7,5,8,9].

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In terms of the technology behind monitoring agricultural conditions, the last decade has seen significant development with the advent of reliable UAV and GPS technologies. Using these technologies in agriculture brought forth a new field called precision agriculture (PA). The concept of PA has emerged in recent years as a farming management strategy. PA assists to monitor, control and receive feedback remotely and constantly from the working field [10]. In the University of Tokyo, a vision-guided tractor with an image-processing algorithm for crops has been developed. This system accurately distinguishes crops from weeds and detects boundary lines between crop and soil areas [11]. Hokkaido University developed a crop row detector which is equipped with a one-dimensional image sensor, this machine detects boundary lines of the crop rows [12]. With the implementation of machine learning, the detection of crop row lines became more precise and accurate [13].

In case of watering, seeding, and weeding processes, only a few robotic systems exist that effectively execute these processes. One notable farming system is the FarmBot Genesis designed by Rory Aronson. FarmBot is based on the movement and tool change of a CNC machine and was released as an open source robot platform. The robot has a multiple tool mounting system, which can be used for seeding, weeding, watering and monitoring soil moisture.

TABLE I. EMPLOYMENT STATISTICS IN THE AGRICULTURE SECTOR (IN MILLION)

	2010	2015	2016	2017
Agriculture workers	2.606	2.097	1.922	1.816
Female	1.300	1.009	0.900	0.849
over 65 years old workers	1.605	1.331	1.254	1.207
Average age	65.8	66.4	66.8	66.7

However, this robot was designed primarily for growing leafy vegetables such as lettuce or spinach [14].

This research proposes an extended version of the FarmBot [14] robot system with harvesting tool, which is based on continuum manipulator TakoBot [15,16]. FarmBot can take care only certain period of time, from seeding until to harvesting, since harvesting process the tool mount system of the robot will be replaced to harvest crops, in this case, robot assumes to collect tomatoes. This research paper will explain the design of both the robot and novel kinematics of continuum manipulator.

II. DESIGN CONCEPT

A. CNC Platform Design

The design of the proposed agriculture robot based on a CNC machine platform. Likewise, robot design makes the environment structured and predictable for the robot, rather than planting in a greenhouse or on the field. Therefore, it has three degrees of freedom, which is well enough for watering, weeding and seeding processes. On Z –axis tip mounted special universal tool mount system for changing tools for watering, weeding, seeding and measuring soil moisture.

As shown in Fig. 3, the farming robot has 4 stepper motors (5), two for the x-axis and single motors for y and z-axes. The base platform of the robot is made from wood (1). The overhead robot frame is constructed with aluminium beams which are supported by corner brackets (2). The gantry (3) serves as the translation along the x-axis which simultaneously holds the aluminium profile (4) for z and y-axes. The cross gantry (6) performs two functions simultaneously: translates motion along the y-axis and holds the z-axis

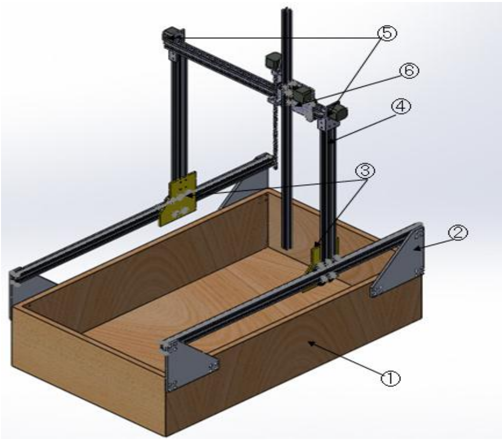


Figure 1. FaRo robot CAD design

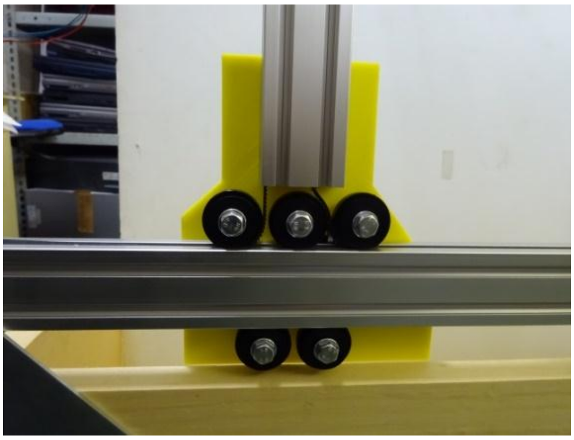
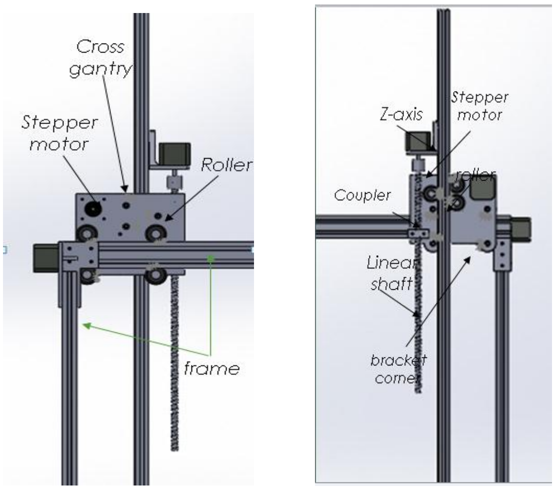


Figure 2. X-axis slider gantry

As shown in Fig. 4, the gantry has five rollers to slide over the profile. The gantry plate had been fabricated by using a 3d printer. One of the issues of the gantry is vibration during motion. So for the next iteration, this component would be replaced by an aluminium plate

The cross gantry (Fig. 5) of FaRo has a more complex design than the gantry. This part is controlled by using two stepper motors for the two axes of the robot, namely y and z-axes. The y-axis of the robot is actuated by using a gt2 belt fixed along the aluminium frame, and z-axes are actuated by using the linear shaft. The motor rotates the linear shaft which translates to motion along the z-axis, and a coupler is attached to the motor as an added support to the system. Gantry sliders are made of ABS plastic and designed in the laboratory.



a b

Figure 3. a) Y-axis gantry b) Z-axis gantry

B. Universal Tool Mount (UTM) System

Tool mount system of FaRo is pretty a complex system with magnetic coupling technology. The universal tool should cover almost all necessary needs, such as provide water, vacuum pressure and even signal Fig [4]. Universal tool is mounted on the tip of the Z-axis profile.

Figure 4.FaRo robot universal tool mount system

UTM mounted with super magnets, which makes an easy coupling system without any mechanical assistance. On the sides of the tools is clearly seen groove, so this groove is designed placing of the tool to the tool bay, after releasing it, groove would be fixed with the tool bay.

Figure 5. FaRo robot tools

The exploitation of tools is simple. Seeder mounted with a thin needle to suck air to pick seed from the pot, soil sensor directly connected to the microcontroller and it requires only signal, ground and voltage pins. Watering nozzle designed as a shower, weeder designed just to kill weeds on the ground.

Figure 6. FaRo laboratory prototype

III. CONTINUUM ROBOT-TOOL DESIGN

Snakes, worms, and slugs have morphologies that can be considered as a hyper-redundant There are numerous set of ways for these creatures to locomote. For instance, slugs locomote through locomotary pulses or pedal waves. Snakes use three primary gaits: lateral undulatory, sidewinding, and concertina modes. This form of locomotion depends on rhythmic expansion and contraction of snakes muscles [17].

From an anatomical point of view, the elephant trunk or octopus tentacle body consists of three main part: vertebral backbone, muscle, and skin. Vertebral backbone presented the main shape of the arm and consist of a flexible spine. Muscles provide motion and skin protect the whole arm from external impact and holds the whole structure. In a mechanical point of view, imitation of the backbone is a challenging and pretty hard to find appropriate material. In this research, we utilize a universal joint and helical compression springs to provide stiffness to the robot (Fig.7).

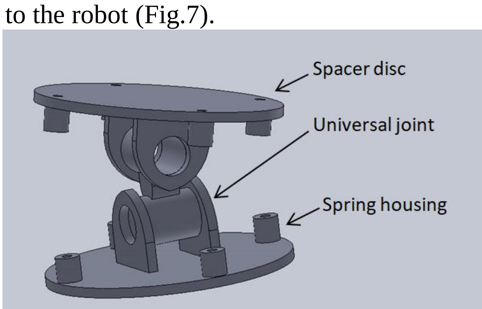


Figure 7. TakoBot single segment design

TakoBot slender part consist of nine segments and each segment are interconnected by 3d printed ABS universal joints (see Fig.8). Between two spacer discs are mounted helical compression springs to provide necessary stiffness to the manipulator (see Fig.9).

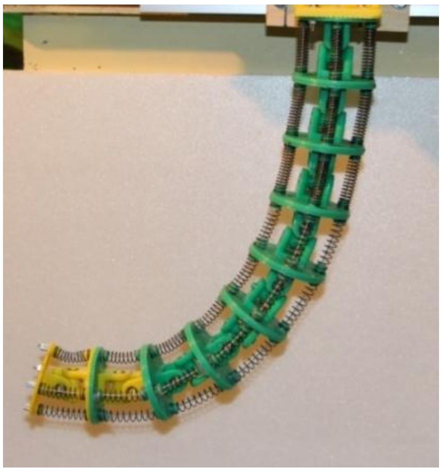


Figure 8. TakoBot . Experimental prototype

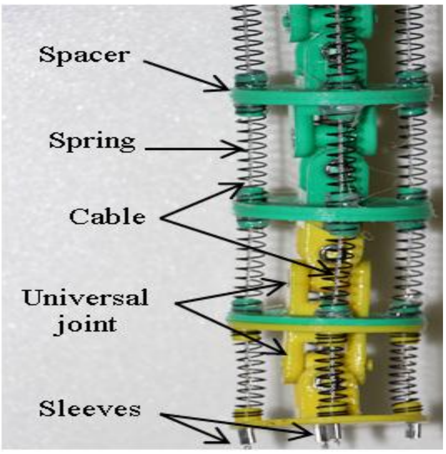


Figure 9. TakoBot structure

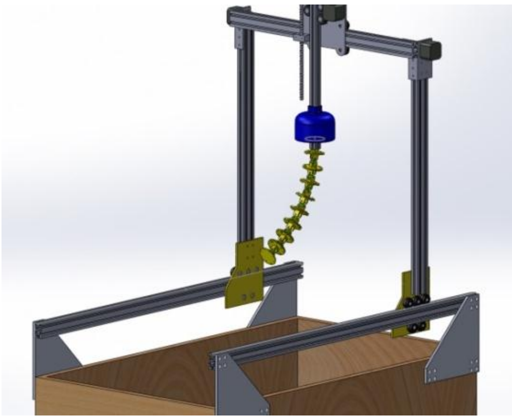


Figure 10. CAD view of harvesting module on FaRo robot

TakoBot actuates by tendon which is connected to the stepping motors. On this prototype only four stepping motors mounted, two motors control tip section, the last two motors control the medium part of the robot. A twin pivot actuation system, one motor control two cables (Fig.11). According to several experiments, the twin pivot system demonstrated the most reliable actuation. Moreover, such a system provides necessary tension for all wires easily rather than single actuation system, and control algorithm would be simple. For this research, we used Arduino CMU and TMC2208 silent stick motor drivers to control stepping motors angle.

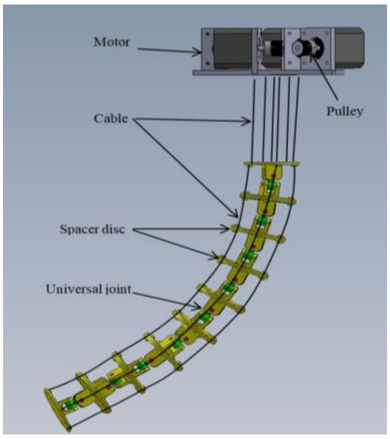


Figure 11. Actuating system

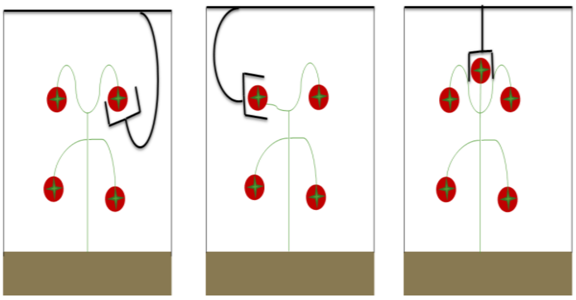


Figure 12. The final application purpose of the TakoBot

IV. Continuum Robot Kinematic Formulation

Fig. 4 illustrates a kinematic model of the continuum robot. It is assumed to have *n* segments, each having rotary axes with a universal joint. Therefore, the model has totally *2n* rotary joints. The positions of the universal joints are represented as U_n ($n=1,\ldots.n$). The robot is assumed to be controlled by 4 wires, the eyelets passing through the wires are represented as A_i, B_i, C_i and D_i ($i=0,\ldots.n$). Coordinate systems are set at every universal joint. Representing $\Sigma_0, \Sigma_1, \ldots. \Sigma_n$ from the base to the tip. The homogeneous coordinate transformation matrices: H- Matrices

$$\Sigma_0 \to \Sigma_1: \boldsymbol{H}_{0,1} = \begin{pmatrix} \boldsymbol{R}_y(\theta_{y1})\boldsymbol{R}_x(\theta_{x1}) & u_1 \\ 0 \quad 0 \quad 0 & 1 \end{pmatrix}, u_{0,1} = \begin{pmatrix} 0 \\ 0 \\ l_1 \end{pmatrix} \quad (1)$$

$$\Sigma_{i-1} \to \Sigma_i: \boldsymbol{H}_{i-1,i} = \begin{pmatrix} \boldsymbol{R}_y(\theta_{yi})\boldsymbol{R}_x(\theta_{xi}) & u_{i-1,i} \\ 0 \quad 0 \quad 0 & 1 \end{pmatrix} \quad (2)$$

$$u_{i-1,i} = \begin{pmatrix} 0 \\ 0 \\ 2l \end{pmatrix}, (i = 2, \cdots, n)$$

where, $\boldsymbol{R}_x(\theta_{xi})$ and $\boldsymbol{R}_y(\theta_{yi})$ are rotation matrices of *i*th universal joint that has two rotation angles θ_{xi} and θ_{yi},

$$\boldsymbol{R}_x(\theta_{xi}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{xi} & -\sin\theta_{xi} \\ 0 & \sin\theta_{xi} & \cos\theta_{xi} \end{pmatrix}$$

$$\boldsymbol{R}_y(\theta_{yi}) = \begin{pmatrix} \cos\theta_{yi} & 0 & \sin\theta_{yi} \\ 0 & 1 & 0 \\ -\sin\theta_{yi} & 0 & \cos\theta_{yi} \end{pmatrix} \quad (3)$$

$2\,l$ is an axial distance between a universal joint and the subsequent one. Multiplying the H-matrices successively, we get unit vectors and the position vector of the *i*th coordinate system;

$$\boldsymbol{H}_{0,i} = \boldsymbol{H}_{0,1}\boldsymbol{H}_{1,2} \cdots \boldsymbol{H}_{i-1,i} = \begin{pmatrix} \boldsymbol{i}_i & \boldsymbol{j}_i & \boldsymbol{k}_i & \boldsymbol{u}_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{4}$$

The position vector $\boldsymbol{p}_n$ of the tip P_n of the manipulator is obtained with,

$$\begin{pmatrix} \boldsymbol{p}_n \\ 1 \end{pmatrix} = \boldsymbol{H}_{0,n} \begin{pmatrix} 0 \\ 0 \\ l_n \\ 1 \end{pmatrix} \tag{5}$$

Position vectors of 4 eyelets $\mathrm{A}_0, \mathrm{B}_0, \mathrm{C}_0, \mathrm{D}_0$ at the base plate are determined as,

$$\boldsymbol{a}_0 = \begin{pmatrix} a_x \\ a_y \\ 0 \end{pmatrix}, \quad \boldsymbol{b}_0 = \begin{pmatrix} b_x \\ b_y \\ 0 \end{pmatrix}, \quad \boldsymbol{c}_0 = \begin{pmatrix} c_x \\ c_y \\ 0 \end{pmatrix}, \quad \boldsymbol{d}_0 = \begin{pmatrix} d_x \\ d_y \\ 0 \end{pmatrix}, \tag{6}$$

Position vectors of 4eyelets $\mathrm{A}_i, \mathrm{B}_i, \mathrm{C}_i, \mathrm{D}_i$ at the *i*th plate are obtained as, (Fig.13).

$$\begin{aligned} \begin{pmatrix} \boldsymbol{a}_i \\ 1 \end{pmatrix} &= \boldsymbol{H}_{0,i} \begin{pmatrix} a_x \\ a_y \\ l \\ 1 \end{pmatrix}, \quad \begin{pmatrix} \boldsymbol{b}_i \\ 1 \end{pmatrix} = \boldsymbol{H}_{0,i} \begin{pmatrix} b_x \\ a_y \\ l \\ 1 \end{pmatrix}, \\ \begin{pmatrix} \boldsymbol{c}_i \\ 1 \end{pmatrix} &= \boldsymbol{H}_{0,i} \begin{pmatrix} c_x \\ c_y \\ l \\ 1 \end{pmatrix}, \quad \begin{pmatrix} \boldsymbol{d}_i \\ 1 \end{pmatrix} = \boldsymbol{H}_{0,i} \begin{pmatrix} d_x \\ d_y \\ l \\ 1 \end{pmatrix}, \end{aligned} \tag{7}$$

$$(i = 1, \cdots, n) \tag{8}$$

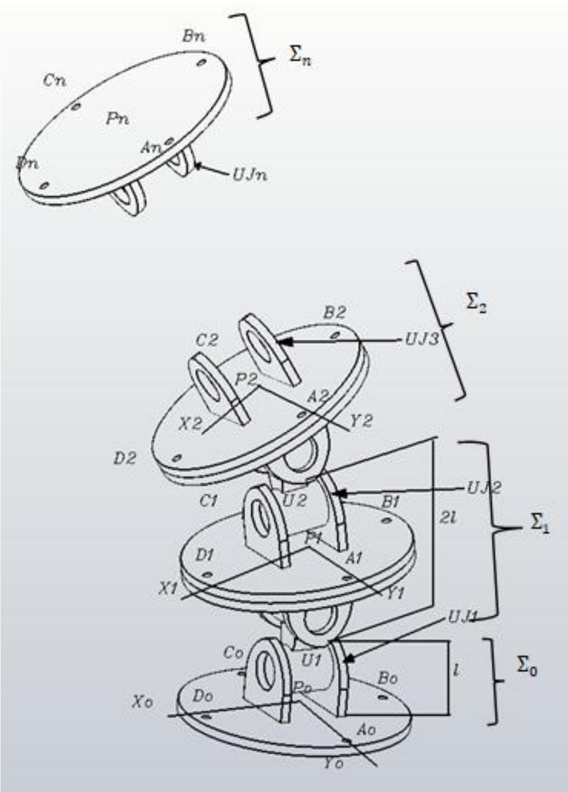


Figure 13. TakoBot kinematic structure

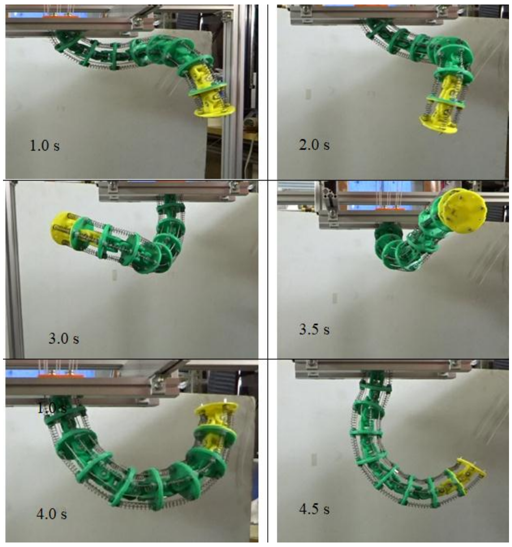


Figure 14. TakoBot experimental timeline motions

V. Conclusion

In this paper, design and kinematics of the harvesting tool of the project has been explained. The design of the robot is still in its development stage due to implementation issues. Future works include adding a bio-inspired harvesting module based on a continuum robot design. A continuum robot hand would help to improve robot features and will improve the robot dexterity as well (Fig.14). Moreover, machine learning will be utilized in the future to execute object recognition in the garden and enhance robot performance in the determination of the crops. The final goal of this project is to complete a prototype with smart farming system module connected to the central database. The robot will have an enough knowledge to plant and grow the crops without human assistance. For the human no need to have knowledge or farming skills to produce vegetables, the robot will have a database to take care of the whole farming process.

Conflict of Interest

"The authors declare no conflict of interest".

Author Contributions

AY wrote the manuscript and conducted research. KK and YY supervised the project and developed the kinematic formulation. LA prepared the robot CAD design. ZB and YA coded the robot. All authors had approved the final version.

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