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DESIGN OF A MOTION SYSTEM FOR 3D PRINTED SNAKEBOT

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A b s t r a c t

This article presents the results of work related to design, analysis and selection of the electric motors, servos and elements of motion system for 3D printed snakebot. Electric motors and servos had to meet a number of requirements like dimensions, torque, RPM. The drivetrain allowed to drive the snakebot and rotate system allowed to torsional movement between adjacent robot modules. CAD model and analysis allowed to select the proper elements of drivetrain and rotate system. We built test stands and after verification we built the prototype. Next step after building the robot was to carry out tests to verify the mobility of the snake robot. We checked, among others, movement of servos in different planes, snakebot speed, driving at angle (up and down).

Introduction

Robotics is one of the industry sector that is developing exceptionally fast. One of the examples of robots that are gaining increasing recognition on the market are snakebots. The names serpentine, modular or chain robot are used interchangeably. The robots resemble a snake, thanks to them have many degrees of freedom, high maneuverability, and a modular structure. Modular construction allows to build snake robots from many similar segments. Individual segments

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are connected to each other by connections with two or three degrees of freedom. They allow to move the mechanism, transfer mechanical forces and torque. Additional elements like grippers, cameras, and sensors are attached to the segments (GILPIN, RUS 2010, p. 38–55, BUCHAN et al. 2012, p. 4347–4354, GRANOSIK et al. 2007).

Serpentine robots are used in urban search and rescue, medicine, and defense industries (REZAEI et al. 2008, p. 191-194, TRANSETH, PETTERSEN 2006, p. 1-8, MOATTARI, BAGHARZADEH 2013, BUCHAN et al. 2012, p. 4347-4354, GRANOSIK et al. 2007, p. 633-662, BORENSTEIN, HANSEN 2007, YIM et al. 2000, p. 514-520, VAN, SHIN 2017). Snakebots gained an advantage thanks to their design. They can easily cope with long and thin spaces, e.g., pipes, ventilation ducts. Their advantage is also the flexibility of connecting individual modules. The connection of each block has several degrees of freedom, thanks to which the snakebots have good maneuverability.

In recent years, 3D printing technology has enabled rapid technological development, especially in the R&D industry (ITUARTE et al. 2016, FIAZ et al. 2019). Additive manufacturing (AM) makes it possible to verify CAD models in a short time and low cost. If necessary, you can quickly make corrections and verify the next versions of the printed elements (ITUARTE et al. 2016, FIAZ et al. 2019, CWIKLA et al. 2017, AYDIN, ESNAF 2019). In robotics, you can also use 3D printing to check the correct operation of mechanisms, connections, dimensional tolerances, and fits. However, the limitations of additive technology should be considered. While some elements can be made quickly and low-cost, their mechanical strength is much lower than in the case of metals or composites (FERNANDEZ-VICENTE et al. 2015, p. 116-128, TAKAGISHI, UMEZU 2017, p. 39852, BENIAK et al. 2017, SELVAM et al. 2021).

CAD model

Concept model

The design works began with the development of several concepts. We assumed that the criteria of the greatest importance would be mobility, so that the snakebot would not get stuck and the rescue operation would not stop. Additionally, we took into account the stability of the robot, easy control, and the possibility of technological manufacturing of the snakebot. Snakebot consist of 3 segments. They are responsible for moving the robot forward and backward. These segments include DC motors, transmission gears, DC motor controllers, and batteries. Each module is driven by eight tracks in pairs at 90 degrees. Between the modules are connectors. They are responsible for the rotation between adjacent modules. Servos and control units are mounted in the connectors. Each connector have two servo drives that will allow for movement in two axes. Bumpers are placed on the front and rear of the robot. In the front bumper, there is a camera and LED diodes responsible for lighting to facilitate maneuvering the snake robot in working conditions and a better view from the camera. At this stage it was also decided to print the snakebot in FDM (FFF) method. We chose that snake robot will be printed with PLA. This filament is not durable, but it is easy in print. It can be useful in case of often corrections in 3D printed models. The designed concept model (Fig. 1) allowed to start next works related to analysis of drivetrain and rotate system.

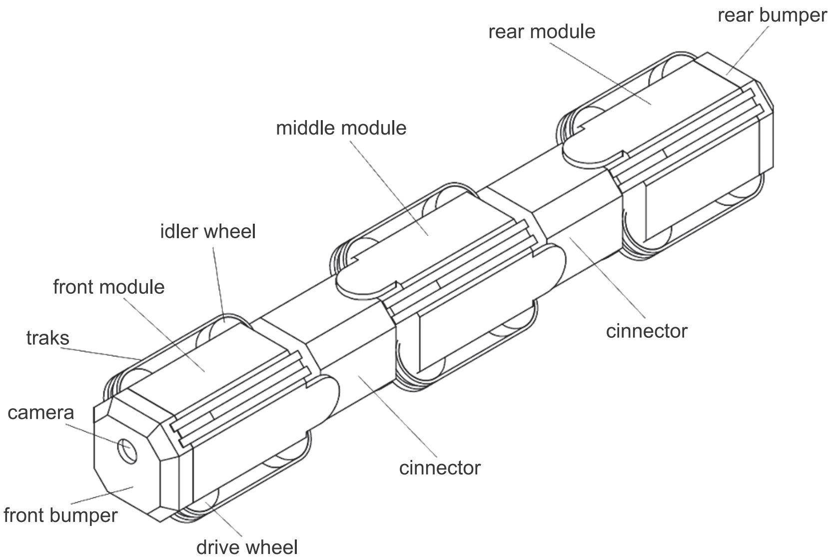

Fig. 1. Concept of snakebot construction

Mechanical system – drive and rotate system

Drive transmission from the electric motor to the tracks is done by two gears – worm and toothed (Fig. 2). The worm gear is constructed in such a way that the torque is transmitted to all tracks thanks to the use of four worm wheels arranged perpendicular to each other (Fig. 3). The worm gear is a reducer and has a gear ratio 25: 1. Additionally, between the worm wheels and the next toothed wheels there is a ratio 1.25: 1. In total, the ratio of the gears themselves is 31.25: 1.

Servos transfer the torque to modules by 3D printed gears and shafts. Rotate system is located in two planes which are placed perpendicularly (Fig. 4). Servos should allow to lift and rotate the modules. This two types of movement ensure flexibility of snake robot and minimizes the robot getting stuck. If the robot overturns, it is still possible to maneuver it in the same way.

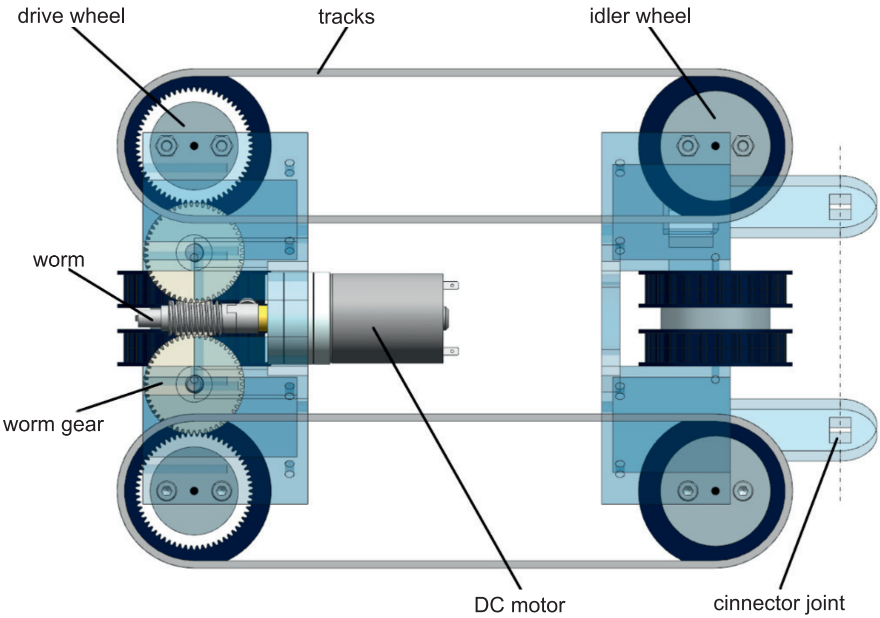

Fig. 2. Operating diagram of the drive system

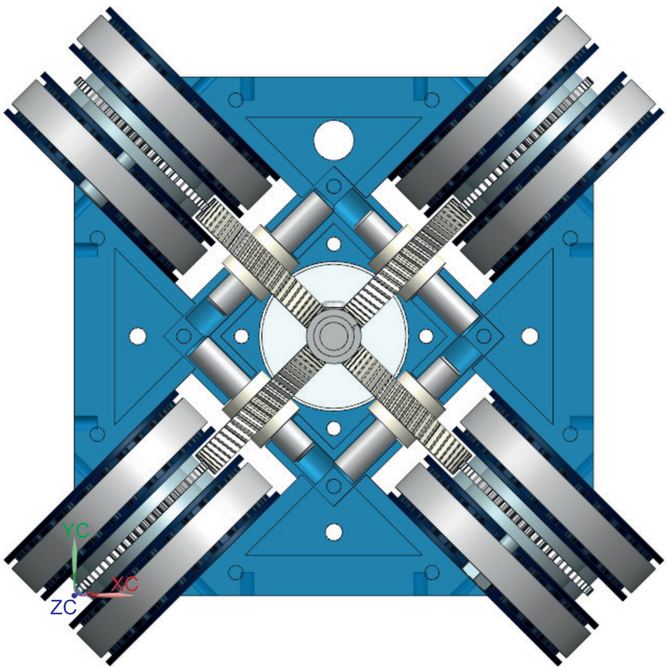

Fig. 3. Front view of the transmission gear

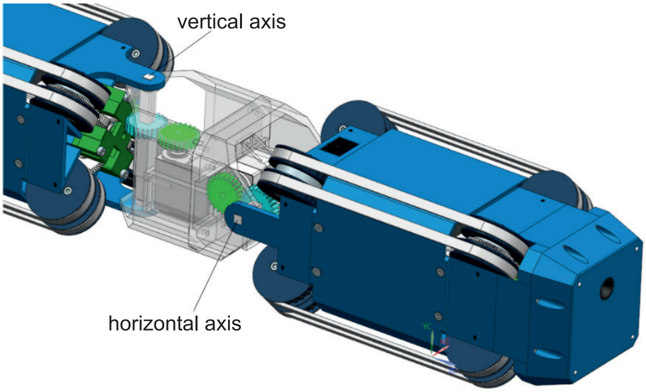

Fig. 4. CAD model of the relative rotation system of modules

Simulation

Snakebot motion simulation allowed to select the electric motors. Dynamic analysis allowed to generate graphs (Fig. 5), so that it was possible to determine what torque must be supplied to the drive wheels. The plot is a sine wave due to the reciprocating movement determined in the dynamic analysis. Middle value that is equal 0.95 Nm is needed torque during start. Torque value decreases with increasing rotational speed and increases when the robot suddenly changes direction of drive (from forward to backward and vice versa). This change in the direction of rotation of the electric motor generates the highest torque of 1.21 Nm.

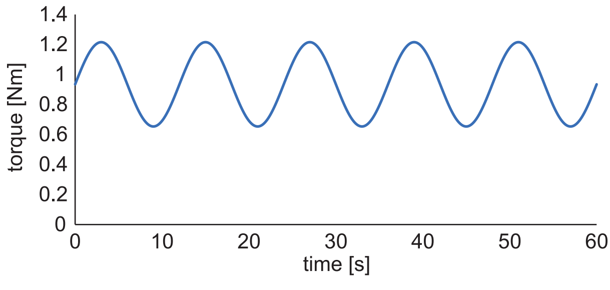

Fig. 5. Torque diagram of the longitudinal drive

After the simulation results, it was possible to select an electric motor that would provide the appropriate torque and rotational speed. We selected motors with a torque of 0.11 Nm and rotational speed 2,150 1/min. Taking into account the snakebot transmission gears, we received torque equal 3.6 Nm and RPM equal ~69 1/min. The 5 mm width tracks are driven by driving wheels with a diameter of 40 mm. It was calculated that the theoretical speed of snake robot will be 144 mm/s.

Dynamic simulation was also made to select the servos. It was necessary to carry out the analysis in two planes, because the system behaves differently in the horizontal axis (Fig. 6) and in the vertical axis. The amount of torque needed to lift the snakebot (horizontal axis) was greater than in the case of the twisting joint (vertical axis). The maximum value of the torque in the analysis was ~0.42 Nm. We selected servo which generate torque 1 Nm and speed 0.14 s/60°.

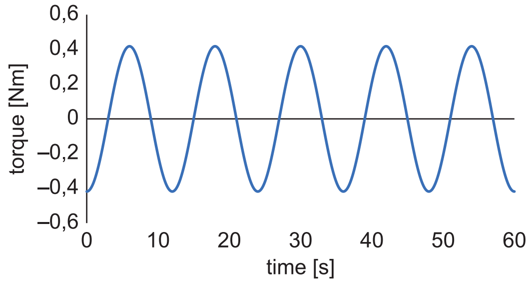

Fig. 6. Torque diagram on the horizontal axis

In the case of a snakebot built of three segments, it was enough to perform an analysis in which the servo lifts one module. Lift of the two segments would create such a torque that the snakebot would topple over.

Verification – mobility tests

Tests were divided into 3 categories. Their purpose was to check the behavior of the snake robot under the assumed operating conditions (Fig. 6). The first group of tasks was to verify how snakebot can cope with various types of ground (Tab. 1).

Table 1

The speed of the snakebot depends on the ground

Type of surface	Rolling coefficient	Velocity [mm/s]	Remarks
Asphalt, Concrete	0.015 - 0.02	80	–
Gravel	0.05 – 0.14	~15	the low ground clearance caused the robot to stop many times
Grass	0.06 – 0.11	–	the soft ground under the grass cause that snakebot stuck
Sand	0.15 – 0.30	–	in the sand, the robot stuck and is unable to move

Fig. 6. Snakebot tests

The second group of tasks checked the maneuverability of the robot and grip. In this test, it was checked whether the robot was able to rotate by a given angle in the vertical and horizontal axes. It was decided to build a test track, which primarily verified the operation of the joints. The developed track contained numerous obstacles that were aimed at verifying the operation of the snakebot connectors. These were, among others elements enabling the snakebot to pass in a slalom and elements verifying the lifting of the modules - small steps/stairs. The test results are presented below (Tabs. 2, 3).

Table 2

Operation of servos in the vertical axis

Angle	Turning radius [m]	Adhesion	Remarks
10°	$r = 1.78$	very good	–
20°	$r = 0.89$	very good	–
30°	$r = 0.6$	very good	–

Table 3

Operation of servos in the horizontal axis

Angle	Does the snakebot lift the main module?	Remarks
10°	–	Buckling of shafts, jump between teeth of gears
20°	–	
30°	–	

The last category of mobility tests was to verify how the snakebot will cope with the differentiation of the terrain, i.e., elevation, slope, depressions (Tab. 4). The test was carried out on a concrete surface.

Table 4

Drive system operation on an inclined surface

Differentiation of the terrain	Does the snakebot drive?	Difficulties	Remarks
Slope 45°	–	–	one module is able to pull the other two
Slope 30°	–	–	–
Slope 15°	–	–	two modules are able to pull one additional module
Flat 0°	–	–	–
Rise 15°	–	heavy load on the drive system	–
Rise 30°	–	very heavy load on the drive system	–
Rise 45°	–	too much resistance prevented the snakebot move	–

Discussion and conclusions

Experiments related to the movement of the snakebot showed that in an environment such as rubble, the snakebot is enable to move and perform maneuvers. Tests performed in many environments have shown that the electric motors and servos were selected correctly. At the beginning of the test the only one problem was drive on the grass and sand. Snakebot was slipping on the grass and tearing out blades and was buried in the sand. The tracks performed well when had a large contact surface with the ground. The servos were able to move in the vertical axis but not in the horizonal. The reason was that resistance was so great that the teeth of the 3D printed gears jumped over each other and the shaft was bending. More problems started after using the robot for a longer time. Some 3D printed parts were more and more damaged, which resulted in dysregulation.

Additive manufacturing makes it easier to build prototypes. However, the design process should take into account the limitations of this method. For some elements, incl. bumpers, spacers, covers 3D printing is great. Other elements such as gears, shafts, wheels did not work that well especially after prolonged use. Continuous, multiple movement of these elements caused misaligned of them. The result was a backlash between the gears, damaged wheels or buckled shafts.

In subsequent prototypes we can change the design of 3D models by changing the cross-section or by using different material. PLA or ABS are much less durable than aluminum or steel. However, they gain an advantage thanks to their low density. In the urban search and rescue, replacing the metal or polymer elements with composite elements e.g., carbon or aramid fiber, can be a solution. Smooth move of snake robot we can increase by using wider tracks and by changing the material of the tracks. In the prototype we used neoprene tracks. It caused skidding and low coefficient of friction with the ground. We should try to reduce the weight of the snake robot by using lighter batteries and DC motors. However, we have to provide the right torque, RPM, voltage, and power.

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