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AUTONOMOUS MULTIFUNCTIONAL VEHICLE WITH INTEGRATED BIO-INSPIRED SMA ACTUATED GRASPER

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ABSTRACT

The space exploration activities are merging new technologies in order to develop systems challenged to achieve capabilities for high mission experience. Inspired by the numerous applications in space exploration, with the integration of shape memory alloys (SMAs), a 3D printed continuous All Terrain Grasper Transport (AT-GT) vehicle with implemented multi-locomotion grasper was created.

In order to reduce failure of the mechanical system, the vehicle is equipped with SMA suspension and SMA tensioner of a pulley system with adaptable height able to achieve movement on a given trajectory and adjust to any terrain. SMA actuators provide controllable actuation based on the simplicity of their design and the shape memory effect.

By using the advantages of the origami engineering, soft robotics and smart material implementation, a bio-inspired autonomous grasper was integrated on the AT-GT, that would be capable of leaving the vehicle, grabbing an object and bringing it back to the vehicle.

The concept development, the analytical models and the prototype including the benefits of the combined work of the vehicle and the grasper are presented.

Keywords: smart materials actuation, bio-inspired vehicle, multi-locomotion, origami engineering, grasper

NOMENCLATURE

m_2, m_{1z}	Mass of the platform and the pulley system
k_{1z}, k_{2z}, k	Stiffness coefficient of the springs
c_z	Damping coefficient
J_2	Inertial moment
z_2, z_{1z},	Displacement
φ_1, φ_2	Angular displacement
F_{in1}, F_{in2}	Inertial forces
F_{k1z}, F_{k2z}, F_k	Spring forces
F_{cz}	Damper force
F_p	Input force
h_z	Input displacement
v	Velocity
n	Number of rotations of the motors
r	Radius of the pulley
M_1, M_2	Resistance moments
M_{in2}	Moment of inertia

1. INTRODUCTION

In order to achieve high mission experience for space exploration, novel technologies are merging for developing systems. Inspired by the numerous applications in space exploration, with the combination of bio-inspired engineering, origami engineering and smart material actuation, complex structures with the high mission ability can be accomplished.

Origami engineering concepts can be implemented in bio-inspired engineering creating designs that often belong to the field of soft-robotics, as shown in [1]. Soft robots have bodies made out of soft and extensive materials (silicone rubbers, polymers and elastomers, and others) that can deform and absorb much of the energy arising from impact, having the potential for adaption, sensitivity and agility [2].The soft-bodied robots can be used in many applications for search and rescue, for limited unreachable places, enabling robust locomotion. Recently, researchers have found their use in space exploration applications [3]. Beyond conventional ones, self-reconfigurable robots are able to deliberately change their own shape by rearranging the connectivity of their parts in order to adapt to new circumstances, perform new tasks, or recover from damage [4]. Long-term sustainability and evolutionary adaptation in nature are provided through processes of self-repair, self-reconfiguration, self-replication and ultimately, self-

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reproduction. [5]. In [6], the researchers have developed bio-inspired soft gripper with capabilities of grasping and holding.

Inspired by the numerous applications in space exploration, with the integration of shape memory alloys (SMAs) and multi-locomotion grasper, a 3D printed continuous All Terrain Grasper Transport (AT-GT) vehicle was created. In order to reduce failure of the mechanical system, the vehicle is equipped with SMA suspension and SMA tensioner of a pulley system with adaptable height able to achieve movement on a given trajectory and adjust to any terrain. SMA actuators and springs provide controllable actuation based on the simplicity of their design and the shape memory effect.

Instead of conventional actuators, the SMA materials can be used to generate force in order to establish movement. The SMA materials have the ability to remember their original form and return it to it using external source. By exposure to an external source, they change their crystal structure and in that process a force is being generated that can be used as an actuator, enabling flexibility and multi-locomotion [7]. The SMAs spring could be easily designed and controlled according to displacement and force requirements. The shape-memory materials exhibit some unique performances, large-stroke actuation, high damping, adaptive responses, shape memory and super elasticity capability, which can be utilized in various engineering approaches in origami-inspired smart applications [8]. Nickel Titanium is one of the most attractive and widely used shape memory alloy material because of its unique functional properties including superelastic (SE) behavior and shape memory (SM) effect, biocompability, low stiffness, corrosion behavior and damping characteristics, enable restoring large strains [9]. Using smart material actuation integrated into 3D printed structure, graspers with unique structure and promising performance have been designed and developed [1, 10]. Smart material actuation is used in bio-inspired concept for the creation of multi-locomotion robot [11].

Using the advantages of the origami engineering, soft robotics and smart material implementation, a bio-inspired independent grasper was integrated capable of leaving the vehicle, grabbing an object and bringing it back to the vehicle. The several movements of the 3D printed grasper like folding, unfolding, crawling and grasping are achieved by combination of flexible and smart materials. The concept development, the analytical models and the prototype including the benefits of the combined work of the vehicle and the grasper are presented.

2. CONCEPT, DESIGN AND FUNCTIONALITY OF THE AT-GT AND THE GRASSPER

Space exploration activities find difficulties while exploration, leading to finding chances of a higher failure of some of the systems. In order to make the exploration easier and more adaptable, All Terrain Grasper Transporter (AT-GT) with integrated grasper was developed, capable of transporting the necessary equipment. The AT-GT has adaptation for any terrain, which is achieved by the implementation of the SMA materials (NiTi springs). A grasper is implemented on top of the transporter, having the possibility of multi-locomotion. Figure 1 shows a CAD model of complete vehicle, consisting of the AT-GT transporter and the grasper.

FIGURE 1: CAD MODEL OF THE AT-GT TRANSPORTER WITH IMPLEMENTED GRASPER

Two main properties of the smart materials used for controlling the model, the capability of remembering their original shape and the thermal resistance. After plastic deformation, they have the capability of returning to their original shape by reaching their transient temperature, which is 65 ºC for the Nitinol springs. By connecting the springs to an electrical source, the springs begin to heat up and reach their transient temperature. Afterwards, the springs begin to contract and the generated force is much higher than the force in the ambient temperature. The characteristic of the SMA to remember their original shape can be used as capability of the device to self-heal or to self-repair, resulting in improving the unexpected problems that may occur while operating the vehicle.

2.1. AT-GT TRANSPORTER

The AT-GT transporter is representing a continuous track vehicle with independent continuous track pulley systems. The entire model is representing a transporter which is capable of carrying entire small laboratory for examining certain specimens and few graspers which would be able to leave the AT-GT to receive those specimens. The entire transporter is being driven by electromotors and the turning of the vehicle is achieved by blocking one side of the AT-GT.

Figure 2 presents the suspension and the pulley SMA systems, where four springs are implemented on each pulley system. Two springs are put between the upper construction and the pulley system and two are positioned on the shaft of the front pulley. This shaft is not rotating, only the pulley is rotating, which acts as a tensioner of the continuous track. When an electrical current is flowing through the springs attached between the platform and the pulley system it contracts, as shown on figure 2.A., the entire upper construction is lowered.

If the springs are activated, the length of the continuous track would not be constant and would result in falling of the wheels. In order to avoid this, there must be correlation between the control of springs. When the previous mentioned springs are being activated, one of the springs attached to the tensioner must be also activated and to pull the entire shaft and wheel in order to maintain the needed length for the continuous truck. This would result in lowering the height of the AT-GT, would allow it to pass under obstacles and the length of the continuous track would remain the same. On the other hand, in order to avoid rougher terrains, the platform must be positioned higher (as shown on figure 2.B). In this case, the remaining spring would be activated and through the previous mentioned it would not flow electrical current.

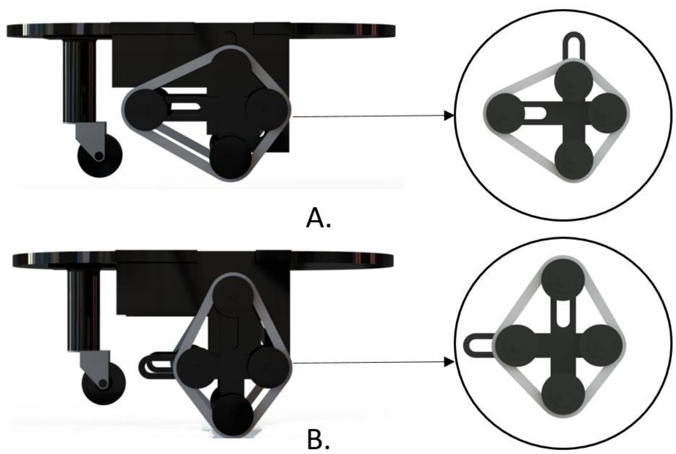


FIGURE 2: CAD MODEL OF THE AT-GT TRANSPORTER (A. LOWEST POSITON ; B. HIGHEST POSITON)

In order to return the AT-GT into highest position, a regular suspension system with specifically chosen parameters is implemented. When the SMA springs responsible for lowering the platform are not activated, the intensity of the forces in the suspension should be higher than the force of the SMA springs and the platform would be at its highest point. When the SMA springs are activated, the forces of the suspension system must have smaller intensity, which would result into lowering the height of the AT-GT. After ending the activation of the SMA spring, it begins to cool and the intensity of its force start decreasing. This would result in returning the platform into the original point (the highest position of the platform), because as the spring is cooling, the forces in the suspension system reach higher intensity than the force in the SMA springs.

2.2. BIO-INSPIRED GRASPER

In order to achieve multi-movement, a bio-inspired grasper was implemented on the upper part of the transporter, increasing the possibilities of the multi-locomotion. The multi-locomotion grasper, as shown on Figure 3, has the capability of passing through a rough terrain and obstacles, as it rolls to the desired object, grasps it and crawls back to the AT-GT. The use of origami engineering and soft robotics with integration of SMA springs was used for the development of the grasper. By creating a large scale deformable body, the grasper has the abilities to resist unpredicted impacts and reach on hard accessible terrains. The actuation of the system is achieved by using SMA springs, which are put through the body on specific spots. These springs are controlled the same way as the smart systems of the AT-GT.

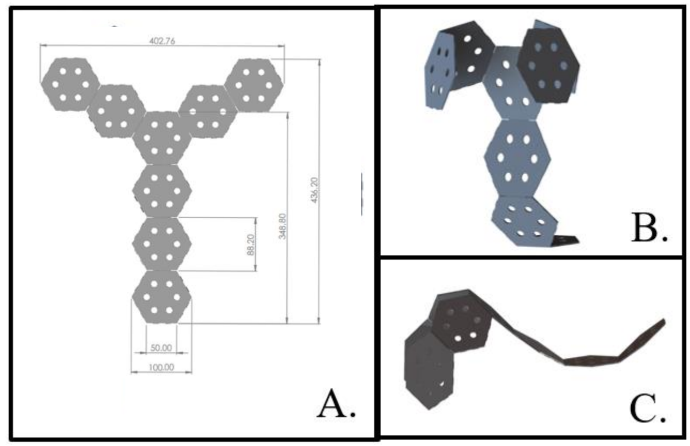


FIGURE 3: CAD MODEL OF THE GRASPER (A. THE GRASPER IN 2D (dimensions are given in [mm]; B. GRASPING; C. ROLLING/CRAWLING)

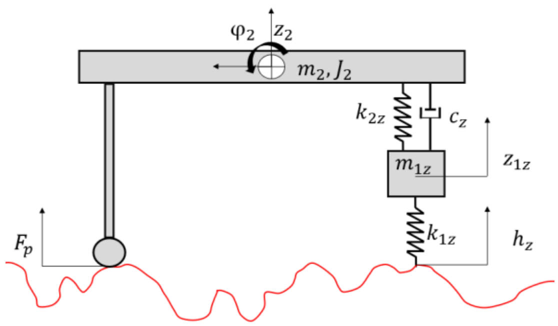
By combining the AT-GT transporter with the bio-inspired grasper, many possibilities allowing great functionality can be established. The AT-GT has the capability of traveling through rough terrain at higher velocity, while caring few graspers. When moving together, the AT-GT and the graspers are connected through magnets that are active only when the AT-GT is moving together with the grasper.

3. ANALITYCAL MODELING

3.1. AT-GT TRANSPORTER

The analytical models for the AT-GT transporter and the grasper are created in the software program Matlab/Simulink, from where the results are analyzed.

Figure 4 shows a simplified mathematical model for the AT-GT, where the vertical dynamics are shown, while Table 1 shows the parameters used for modeling. The mathematical model has three degrees of freedom (DOF), showing the vertical movement of the platform z_2, the rotation of the platform around the center of mass φ_2 and the movement of the SMA pulley system z_{1z}. As it can been seen from the concept before, the AT-GT has two SMA pulley systems and one frontal passive wheel which is stiffly connected to the platform. An approximation in the model has been made, that the rear smart tracks are represented by one single axle. The entire mass of the upper platform (m_2) is situated in the center of the mass of the upper cantilever. The suspensions system of the SMA pulleys are represented with the mass of the system (m_{1z}), the stiffness of the SMA springs (k_{2z}) and the damping coefficient (c_2). The continuous track is shown by the stiffness coefficient (k_{1z}).



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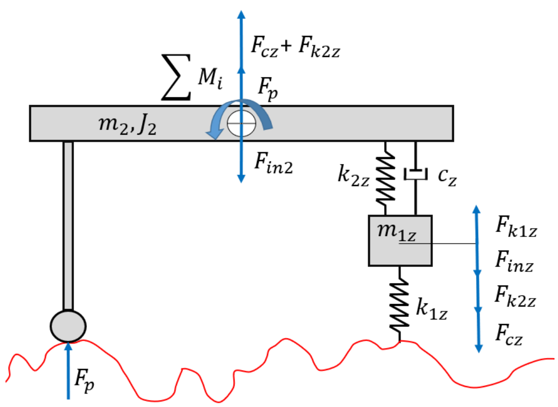


B.

FIGURE 4: MATEMATICAL MODEL OF THE AT-GT TRANSPORTER (A. INPUTS OF THE SYSTEM AND IT'S DOF; B. FORCES AND MOMENTS THAT INFLUECE THE RESPONSE FROM THE SYSTEM)

TABLE 1: PARAMETERS USED IN THE MATHEMATICAL MODELING

$F_{k1z} = k_{1z}(h_z - z_{1z})$;	Force in the contact between the road and the continous track
$F_{k2z} = k_{2z}(z_{1z} - z_{2z})$	SMA spring force
$F_{cz} = c_z(\dot{z}_{1z} - \dot{z}_{2z})$;	SMA damping force
$F_{in1} = m_{1z}\ddot{z}_{1z}$; $F_{in2} = m_2\ddot{z}_2$;	Inertial forces
M_{in2}	Moment of inertia
$J_2 = m_2 i^2$	Inertial moment
F_p;	Input force on the front axle
h_p;	Input displacement from the road
z_{1z}, z_2;	Displacement of the pulley system and the upper platform
φ_2;	Angular displacement of the upper platform
$k_{1z} = 1$ N/m	Stiffness coefficient of the continuous track
$k_{2z} = 65/10$ N/m	Stiffness coefficient of the SMA spring (heated/ not heated)
c_z=10 Ns/m	Damping coefficient of the SMA spring
$m_{1z} = 0.1$ kg $m_2 = 1$ kg	Mass of the pulley system and the upper platform

In order to stimulate the system, different inputs that depict different road configuration, have been modeled for the SMA axle, which represent one of the inputs of the system h_p. The second input is represented by a force F_p, which represents an impact force form the road, due to the stiff connection between the axle and the platform. This impact force is modeled emphasizing factor of 1.5 of the static load of the front wheel. The equations below present the three force and moment equations:

$$F_{inz} + F_{k2z} + F_{cz} - F_{k1z} = 0 \quad (1)$$

$$F_{in2} - F_p - F_{k2z} - F_{cz} = 0 \quad (2)$$

$$M_{in2} + F_p l_p - F_{k2z} l_z - F_{cz} l_z = 0 \quad (3)$$

In order to create a state-space format of the model, three equations were included $\dot{\varphi}_2 = \varphi_4$, $\dot{z}_2 = z_4$ and $\dot{z}_{1z} = z_{3z}$ and together with the differential equations derived before, a state-space format of the model was created and fully defined:

$$\begin{cases} \dot{z}_{3z} = -\frac{(k_{1z}+k_{2z})}{m_{1z}} z_{1z} + \frac{k_{2z}}{m_{1z}} z_2 + \frac{k_{2z} l_z}{m_{1z}} \varphi_2 - \frac{c_z}{m_{1z}} z_{3z} + \frac{c_z}{m_{1z}} z_4 + \frac{c_z l_z}{m_{1z}} \varphi_4 + \frac{k_{1z}}{m_{1z}} hz \\ \dot{z}_4 = \frac{k_{2z}}{m_2} z_{1z} - \frac{k_{2z}}{m_2} z_2 + \frac{k_{2z} l_z}{m_2} \varphi_2 + \frac{c_z}{m_2} z_{3z} - \frac{c_z}{m_2} z_4 - \frac{c_z l_z}{m_2} \varphi_4 \\ \dot{\varphi}_4 = \frac{k_{2z} l_z}{J_2} z_{1z} - \frac{k_{2z} l_z}{J_2} z_2 - \frac{k_{2z} l_z^2}{J_2} \varphi_2 + \frac{c_z l_z}{J_2} z_{3z} - \frac{c_z l_z}{J_2} z_4 - \frac{c_{2z} l_z^2}{J_2} \varphi_4 - \frac{F_p l_p}{J_2} \end{cases}$$

The velocity of the vehicle has to be defined in order to model the delay of the inputs that are in direct relation with the wheelbase and the velocity: $\Delta t = l/v$. The velocity $v = f(n, r)$ depends of the number of rotations (n) and the radius of the shaft (r) of the pulley system. When the batteries of the AT-GT are at full load and the maximum rotation $n_{max} = 90\ min^{-1}$ of the motors is achieved, the maximum velocity would reach $v_{max} = 0.2\ m/s$.

Figure 5 shows the results of the mathematical model, where the road excitation is shown. In order to compare the results from the experiments, the velocity of the model was $v = 0.074\ m/s$ and the number of rotations of the motors were $n = 33.75\ min^{-1}$. The simulation and the experiment were conducted by stimulating the system with a step function.

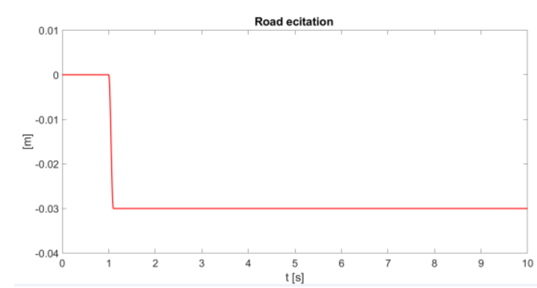
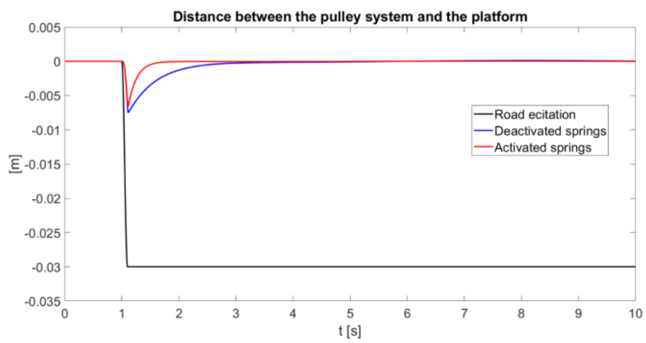
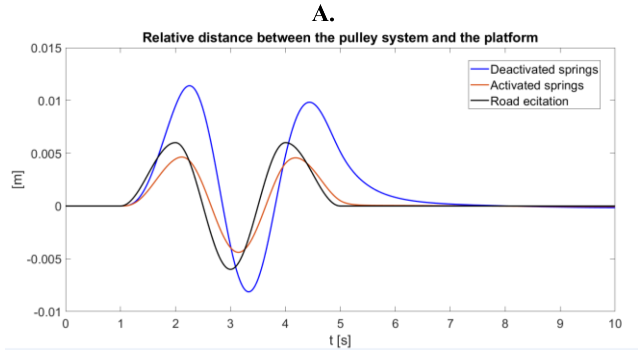


FIGURE 5: ROAD ECITATION (STEP FUNCTION)

Figure 6 shows the differences when using SMA springs, where it can be seen the benefit of allowing the AT-GT to adapt its height. Figure 6.A shows the relative distance between the platform and the pulley system from the input shown on Figure 5, while 6.B. presents the reaction of the system for movement on rough terrain with sinusoidal profile. When the springs are activated, the stiffness of the system is increased which result in smaller relative distance and the oscillations of the system will come to idle faster. The graph of the deactivated springs represents only the passive system, which is implemented to the prototype.



A.



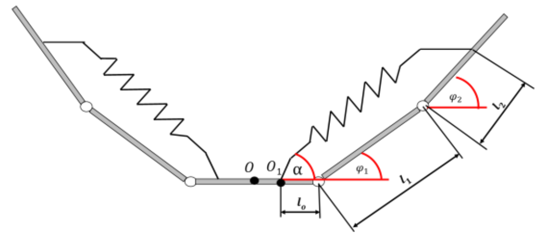
B.

FIGURE 6: RESULTS FROM THE MATHEMATICAL MODEL SHOWING RELATIVE DISTANCE BETWEEN THE PULLEY SYSTEM AND THE PLATFORM (A. USING INPUT ON FIGURE 5. USING SINUSOIDAL ROAD PROFILE AS INPUT)

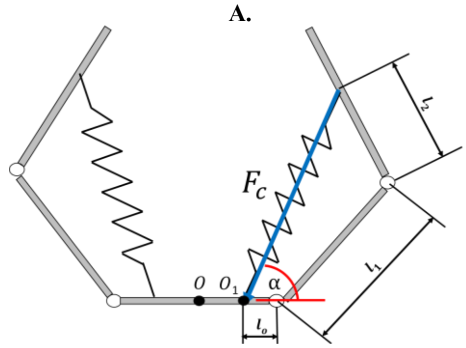
If multiple smart springs are implemented to the model, the oscillations of the system will be reduced, so as the chances of damaging the electronics and the elements, due to the fact that prolonged oscillation may cause fatigue of these systems. Another advantage is that, if the terrain before the AT-GT is scanned and the suspension is being adapted to it, the smaller oscillation will reduce the chances of hitting an object under or above the AT-GT because of the smaller reaction delay.

3.2. BIO-INSPIRED GRASPER

After modeling the AT-GT, a mathematical model for the grasper was made, as shown on figure 7. The grasper can grab an object from both sides using the length of its arms and the actuator force of the SMA spring. Each arm is consisted of two sections with length *l* and the spring is attached on the end of the segments. The springs are attached at distance of *0.3l* from the end of the segment, while the other side of the spring is attached at *0.5l* from the hinge between the two segments.



A.



B.

FIGURE 7: MATEMATICAL MODEL OF THE GRASPER (A. PRESENTS POSITION BETWEEN GRASPING AND UNFOLDED MODEL B. PRESENTS THE GRASPING POSITION)

The following equations show the moment equation of the necessary force *F* that is needed to overcome the resistance forces of the hinges:

$$Fcos\,(\alpha)y - Fsin\,(\alpha)x - M_1 - M_2 = 0 \quad (4)$$

$$x = l_1 sin\varphi_1 + l_2 sin\varphi_2 \quad (5)$$

$$y = \frac{l_0}{3} + l_1 cos\varphi_1 + l_2 cos\varphi_2 \quad (6)$$

Through an experiment it was shown that the SMA springs poses nonlinear characteristic and through approximation it can be stated that the springs used in this research have linear stiffness coefficient: *k=65 N/m*. This approximation was done in order to simplify the used mathematical models. Figure 7 shows the necessary force F, needed for lifting the grasper from a flat position, and generated spring force F_k, when the spring is activated, shown as function of the angle φ_2. It can be noticed that the actuation force F_k is higher that the necessary force F after the bending of the segments of angle, but it can not overcome the resistant force before angle.

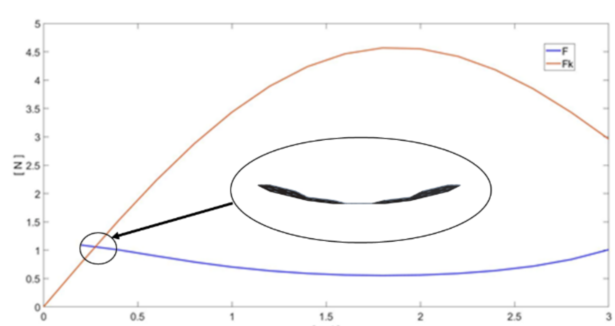


FIGURE 8: THE DEPENDENCE BETWEEN THE NECESSERY FORCE F AND THE GENERATED SPRING FORCE F_k, WHEN THE SPRING IS ACTIVATED

The SMA spring could not lift the grasper's arm from completely flat position until angle of $\varphi_2 = 15.75°$ is established. After that, as it is presented in figure 8, the intensity of the SMA spring is higher than the minimal needed force for lifting.

4. PROTOTYPING

4.1. AT-GT TRANSPORTER

After the analytical modeling, a prototype for the vehicle was made, and the results from the measurements were compared. Figure 9 shows the AT-GT, where it can be seen that the dimensions are same as the ones used for the analytical modeling. The prototype of the AT-GT was printed using the additive manufacturing technologies. The transporter is consisted of microcontroller, two TT motors, while the controlling was established via Bluetooth module. The power supply for the system was from 9V battery. At full capacity of the batteries, the motors can rotate approximately of 90 rotates per minute and generate torque of around 0.98 Nm.

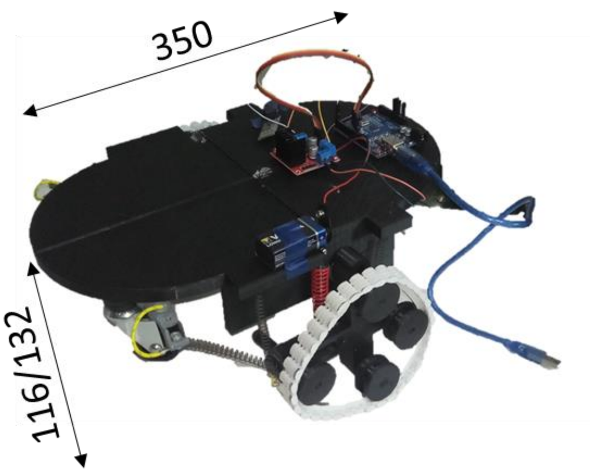
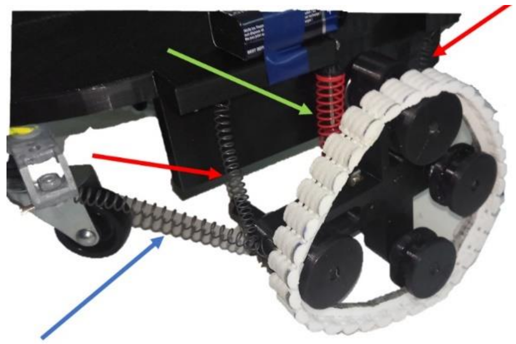


FIGURE 9: PROTOTYPE OF THE AT-GT (DIMENSIONS ARE GIVEN IN mm]

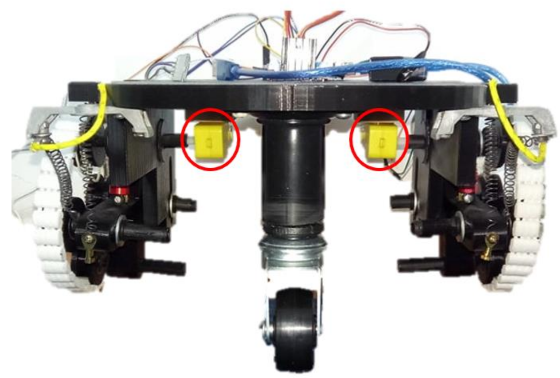
Figure 10.A shows the SMA pulley system consisted of four SMA springs, one spiral spring and one damper, while figure 10.B. shows the position of the servo motors. The two springs, pointed with red arrows are used for lowering the upper platform, so when activated, they contract and the force that is generated in the springs is higher than the passive spring and damper. This results in lowering the upper platform and the entire height of the AT-GT. When the springs cool down, the forces of the passive spring and the damper are higher than the forces in the smart springs, so the AT-GT will return in its original position.

The other two smart springs are connected to the shaft of the front pulley which also represents a tensioner. In order to maintain the same length of the continuous track, when the two SMA springs, depicted by red color, are activated, the front spring is activated and pulls the front shaft and pulley. In the opposite situation, when the vertical springs are cooling down, the rear spring, which is not depicted on the figure, is activated and pulls the shaft to the back into position suitable for the highest point. In this way, the height of the AT-GT is being changed and the length of the continuous track remains the same. For the control of the springs, an electrical coil with 9V and high amperage capability was used.

During the prototyping, a conclusion was made, indicating that the system must be able to withstand high amperage, because only one spring required 2.5 A of current. In order to control the entire SMA system simultaneously, minimum of 15 A of current is required in the system, due to the fact that we use three springs per one pulley system at a time and the AT-GT poses two SMA pulley systems. Because of this the necessity of a powerful controller is mandatory.



A.



B.

FIGURE 10: A.POSSITION OF THE SMA SPRINGS; B. POSITION OF THE SERVO MOTORS

It is important to mention, if one of the SMA suspension system is being observed, only the upper shaft is connected directly to the motor and the pulley rotates together with the shaft. Also, that is the only pulley that is not performing any translations, only rotation. The other pulleys are connected to the shafts with bearings, which means that only the pulleys rotate, while the shafts are used for moving the pulleys in the desired direction by the SMA springs. This simplifies the connections between the springs and the shafts and simplify the mechanism of the pulleys, while the length of the continuous track remains the same.

After constructing the vehicle, a measurement for the velocity was made, where it was confirmed that the speed of the AT-GT is 0.074 m/s. In both of the approaches, the analytical modeling and the experiment, as input to the system was used step function shown on figure 5.

As it can be seen on Figure 11, the maximal acceleration is 5 m/s^2, where more oscillations can be noticed in the experimental data.

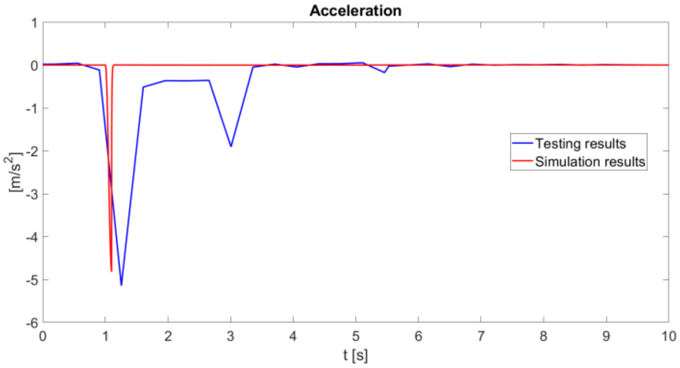


FIGURE 11: EXPERIMENTAL DATA OF ACCELERATION

4.2. BIO-INSPIRED GRASPER

In order to create multi functional vehicle, two different concepts were merged as the bio-inspired grasper was added on the AT-GT transporter. The grasper was 3D printed using flexible material like single structure, while the segments are connected through hinges, as shown on figure 13. Two springs per arm were implemented and another two springs were positioned, so the grasper could lift the upper part together with the object. The length and the thickness of the hinges was properly designed, so the resistant forces and moments that are generated are higher than the forces of the springs when they are not activated. This means that if the springs are not activated, the grasper would return into its original 2D position, simplifying the entire assembly. By activating different springs, several positions of the grasper can be achieved.

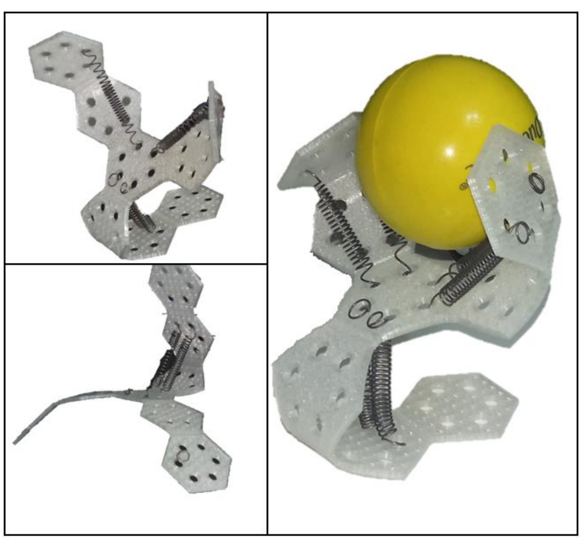


FIGURE 12: GRASPER IN SEVERAL MOVEMENTS

On Figure 13, the final prototype where the AT-GT and the grasper are set together is shown.

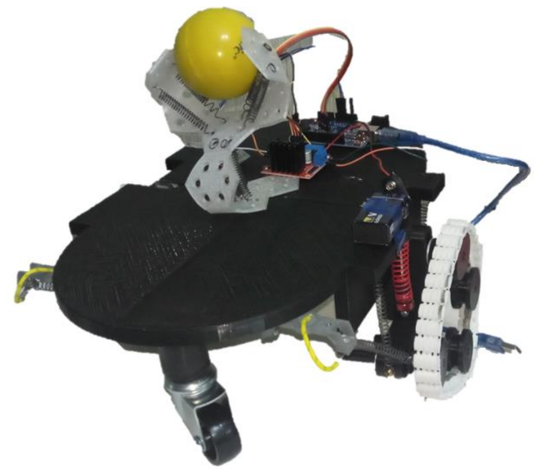


FIGURE 13: FINAL PROTOTYPE OF THE AT-GT WITH IMPLEMENTED GRASPER

By combining the AT-GT together with the grasper, smart structure the high functionality is achieved, allowing multi-locomotion, multi-movement and flexibility.

5. CONCLUSION

Combining multiple approaches such as multi locomotion, smart material actuation and bioinspired engineering, leads into creating trendy solutions offering new levels of flexibility. The implementation of a SMA pulley system for the AT-GT makes the transporter capable of adapting its height for a rougher terrain and the reliability of the system is increased, because SMA materials have the capability of returning to its original shape.

If the positions of the springs are combined differently, we will be able adapt the same grasper for executing another function. This means that one segmented body can be adapted for different roles and more of this robot can be placed on the AT-GT. The Nitinol springs are easy to control using electrical supply, but the controller that would be used, must be capable of withstanding higher amperage, otherwise the controller itself can be damaged or the connection may be destroyed. To improve this entire system, implementation of cooling system that would cool the SMA springs faster might be implemented.

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