Design, manufacturing and testing of re-configurable crawling modular robot inspired from origami

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Abstract. This paper proposes a new type of origami inspired modular crawling robot that can be used for search and exploration purposes. Origami is an art of paper folding where a 2D sheet of material is folded into a 3D robotic structure. The origami inspired design introduces a low cost manufacturing technique and hence reducing the overall cost of the robot. This robot also has characteristics of modular robots. These robots can be connected, disconnected and re-connected to obtain different configurations. The prototype of the robot is manufactured and two types of crawling locomotion are implemented. Various test cases were created and tested under laboratory conditions. The robot was also tested to validate the characteristics of origami robots, modular robots and crawling locomotion is also implemented in unstructured environment. The first section in your paper

1. Introduction

Research has been conducted in the field of search and explorer robots for the past decade, especially in developing narrow search robots [1]. Narrow search robots are small robots which are used in narrow search operations (searching small and compact spaces). These narrow search robots are very small and have complex locomotion strategies. These robots are bioinspired and have complex design inspired from living organisms such as snakes, earthworms and inchworms. These organisms obtain their locomotion through crawling. Crawling locomotion is a type of prone locomotion which is a specific mode of locomotion where the abdominal part of the organism is in contact with the surface. Developing a crawling locomotion is a complex process which involves a periodic shift in inter-limb coordination to propel the body forward. In order to overcome the complexity in design and manufacturing, an origami inspired design has been introduced for developing the robot.

Origami is a newly introduced technique in the field of robotics [2]. It is basically a Japanese art of paper folding where a sheet of paper is folded into different shapes. Origami inspired design can reduce the manufacturing time and overall cost of the robot. Origami inspired design when implemented in modular robot can improve the re-configurability of the robot, because origami based designs are simple, thin and less complex in structure. Origami can turn a single 2D sheet of material to be folded into a useful robot that perform a specific task.

Modular robots are a special type of miniature kinematic machines or robotic units that have a variable morphology [3]. These miniature robots can connect, disconnect and re-connect to accrue different shapes to perform different tasks. These robots are fully functional in the
situations where the environment is unknown and are very compact. These robots can adapt to change its configuration automatically based on different environments to perform specific tasks. These robots, unlike other robots are small, compact and it uses crawling as a mode of locomotion to carry out search and rescue process in very narrow spaces.

The work contributes a new robot which has the combined characteristics of origami and modular robots. The proposed robot can carry out narrow search operations in unstructured and dynamic environments. These robots can connect and re-connect with other modules to form different 3D shapes. The robot mainly uses crawling locomotion and it can perform two modes of crawling locomotion as depicted in Fig.1 and Fig.2. This new robot overcomes the limitation of existing search robots especially in performing narrow search operations.

This paper is systematically organised into sections, where section II contains the related work which are carried out in the fields of origami, modular robots and crawling locomotion’s. Section III covers the design principle and mathematical modelling of the robot. Section IV covers the manufacturing, which includes both mechanical and electrical parts of the robot. Section V covers the simulation and control of the robot. Section VI contains experimental verification and testing of the robot. Final section concludes the paper and validate the proposed system and future work.

The main work that has been contributed in this paper are:

• A new crawling robot inspired from origami which can perform two modes of crawling locomotion’s.

• Developing a prototype of proposed system, maintaining the key characteristics of origami folding and modular robots.

• Experimental validation of robot for two modes of locomotion to carry out search operation on different terrains was carried out in laboratory conditions.

2. Related works

Origami a Japanese art which came into existence from the invention of papers was mainly used for religious and ceremonial purposes. For the past few years this art of paper folding is transformed and various paper folding technique was used in food industries for packing food. Initially this technique was carried out by bare hands, later this technique was automated using manipulators for folding [2]. This manipulator was able to carry out all paper folding techniques such as flat folding, squash folding, petal folding, valley folding, reverse folding and prayer folding [2]. Origami based approach was also introduced in developing deformable wheels
These origami inspired wheels can shrink their size depending upon different terrains to carry out locomotion. Another approach towards introducing origami was to introduce a simple fabrication method with which robots can be manufactured easily with less time and in a cost efficient way. This fabrication method uses simple materials such as sheet of paper or cardboard, which can be easily structured into different shapes. The origami based design and manufacturing provided robots that are faster, cheaper and easier to fabricate than robots created using traditional manufacturing processes.

Modular robots are a special type of robotic system that have a variable morphology. In these, multiple modules together can connect, disconnect and re-connected with other modules to form various configurations to perform some special task. Individual modules can be attached to other modules in chain or in lattice configurations; these systems can be heterogeneous or homogeneous in nature. Homogeneity of modules is that the module are identical. Advantage of the modules being homogeneous is that defective modules can be easily replaced with fully functional modules. Heterogeneous modules are complex as they have different sets of module that perform different tasks. In this a pair of units can only be connected with each other. There are many modular robots developed with one or other novel features. When conducting research on previously published designs some factors were considered such as: housing design, attachment strategy, mobility, communication and power.

Different studies have been conducted in developing miniature robots that have a novel locomotion. Mobility of a robot is very important as dynamic nature of the robot increases the DoF and functionality of the robot. There are various types of locomotion such as legged, wheeled, float, flight and crawling. Different locomotion’s are suited for different types of environment such as wheeled locomotion suited for structured environment, legs are suited in unstructured and float suitable in viscous environment. Developing locomotion of miniature small robots is a tedious task so most of these robots uses crawling as a form of locomotion. Many crawling robots have been developed. These robots possess different types of crawling. There are mainly two types of crawling peristaltic crawling which is mainly seen in earthworms and two-anchor crawling which can be seen in inchworms. Fig. 2 shows the crawling locomotion which are mainly seen in earthworms and Fig. 1 shows two-anchor crawling mainly seen in inchworms. Peristaltic crawling is a type of crawling where body of the organism is divided into segments and these segments contract to develop a lateral motion to move forward. Two-anchor crawling is a type of crawling where the organism obtain omega shape to inch forward. Different variety of crawling robots have been developed which have a complex design and have a form of crawling locomotion. Origami based approach in developing design has reduced the complexity in manufacturing and in generating two different types of crawling locomotion.

3. Robot design

3.1. Design Principle

This section mainly deals with the design and mathematical model used in developing the origami inspired crawling modular robot. This robot has both characteristics of origami robots and modular robots so it has some special features in design. The key design features of the robot are as follows:

- Size of the robot is small. Reduced size of the robot increase the re-configurability of the robot and are efficient in narrow search operations.
- Robots are modular in nature, each module have identical connecting, disconnecting and re-connecting mechanism.
Robots are re-configurable, have features of modular and origami robot so it can connect with each other and can shift their shape form 2D to 3D.

- The module are able to move from one point to another point with efficient crawling locomotion.
- Modules can communicate with other modules, and have inter module communication.
- Since these robots are small and are dynamic in nature these robots have a dedicated power supply and it can work for 15 minutes.

Design of the origami inspired crawling modular robot was developed by studying the basic mathematical geometrical shapes. The main advantage of considering rectangular shape is, the rectangular shape has two identical sides and all the modules can be connected easily and more efficiently. Introducing the rectangular design the robot can easily form chain and lattice configuration and maximum re-configurability of the robot can be obtained. The overall size of the robot is very small that the whole robot can be enclosed in hand. Full body of the robot is divided into two parts flap’s and centre body. The flaps are connected to the centre body using flap connectors. The gradual moment of the flaps generate robot motion. The CAD model of the full robot have been developed using Solid work software and shown in the Fig.3. It shows the various robot components which are assembled to form a complete robot.

![Figure 3. Schematic view of the robot.](image)

![Figure 4. Top view of silicon friction pads used to generate friction for robot to crawl.](image)

![Figure 5. Side view of silicon friction pads used to generate friction for robot to crawl.](image)
3.1.1. Flaps
The extended part of the robot, which support in generating motion and in obtaining re-configuration of the robot. These flaps support the overall robot on the ground, acting as two legs for the robot. Its design is developed considering the geometric square shape having grinded edges. These flaps are connected to the actuator using flap connectors.

Two friction pads are connected to the ends of the flap to generate extra friction for generating locomotion. The overall sides of the flaps have 100mm in length and have thickness of 6mm as shone in the Fig.3. Structural analysis of the flaps were carried out by considering the flap as a cantilever beam and it was found that the maximum stress occurs at the flap connectors. These joints were reinforced with aluminium to increase the strength of the flaps. The Fig.6 and Fig.7. Shows the analysis performed on the flaps of the robot to calculate stress and total deviation of the flaps.

3.1.2. Friction Pads
This robot uses crawling as a mode of locomotion and the crawling locomotion is mainly based on friction produced during motion. In order to develop friction during motion a special type of anisotropic friction pads were developed. The friction pads are anisotropic, it can vary friction depending up on the applied force. This setup is extremely helpful for the robot to crawl without any active gripper. It is made of silicone rubber of which a side is covered with low friction material. The friction pads are depicted in the Fig.4 and Fig.5. The friction pad have outer diameter 9mm, inner diameter of 4mm and overall height of 12mm. The cylindrical design has been filleted on one side and the centre part is a hollow cylinder for fixing it on the flaps of the robot. This friction pad act as the basic functional unit to generate motion.

3.2. Modelling
This section describes about the kinematic modelling of the robot. In order to develop the kinematic model certain assumptions were taken. The whole robot is placed on a concrete surface as shown in the Fig.8. The two ends of the flaps are in contact with the surface. The flaps are arranged such that when connected the end points forms a triangle as shown in Fig.9. The term \( l \) is the length of the flap, \( x \) is the distance between the flap and \( \theta_1 \) and \( \theta_2 \) are the angle between flaps and the concrete surface. The robot place on the concrete surface generate a triangular structure when we join all the points. In the triangle PQR draw a perpendicular from P to N.

![Figure 6](image6.png) Effect of equivalent stress on the flaps when a force is applied at the ends of the flap.

![Figure 7](image7.png) Total deformation of flap when a force if applied at the ends of the flap.
From the Fig.9 triangle PNQ and triangle RNQ we get,

\[ PN = l \cos \theta_1 \]  
\[ RN = l \cos \theta_2 \]  

We know that \( x \) is the distance between the two flaps and is equal to \( PR \), where \( PR = PN + RN \).

\[ x = l \cos \theta_1 + l \cos \theta_2 \]  

Step size during crawling locomotion for each cycle can be calculated as.

\[ \Delta s = x_f - x_i \]  

Where \( x_i \) and \( x_f \) are the initial and final distance between the flaps of the robot, \( \Delta s \) is the step size of the robot during crawling locomotion. Displacement of the robot in \( s \) direction can be continuously obtained by

\[ s_i = \Delta s + s_i - 1 \]  

Where \( s_i \) and \( s_{i-1} \) are the initial and final position of flaps of the robot in the direction of motion.

4. Manufacturing

This section deals with the manufacturing of the robot, it also explain about robot body and electrical circuitry of the robot. The structure of robot is manufactured using 3D printing and hand crafting. The electrical circuitry describes about the type of controller used for developing the controller board. This section also explains the communication protocol used in developing communication between the servo and controller board.

4.1. Robot Body

Manufacturing of this robot is simple compared to other crawling robots. It uses 3D printing and hand crafting technique for manufacturing of the robot. A special type of material called PLA (polylactic acid) is used for 3D printing. These PLA are biodegradable polymers which are produced from lactic acid and have a melting point between 180\(^\circ\)C to 220\(^\circ\)C. The clamps of the robot for holding flaps of the robot are 3D printed. The flaps of the robot are fabricated using material called PVC resin. PVC resin boards are light weight and have laminated surface. These boards have cell structure which are very close making it light and brittle. These board have
thermoplastic property and softens at 148°C and the density varies from 48kg/m³ to 400kg/m³. For manufacturing the full body of the robot PVC resin of 6mm thickness is used. The flaps and servo holder is fabricated by cutting, grinding and reshaping the PVC resin boards. The serial smart servo is bolted to the servo mount using a servo clamp and glued using epoxy to increase the bonding strength. Clamps for fixing the flaps are connected to servo connectors and the whole servo connector with the clamp is connected to the smart servo.

4.1.1. Friction Pads
The gripping pads used for generating friction are made of silicone rubber, which are mainly synthetic rubber and have good resistance to heat and other chemicals. The advantage of using silicone rubber is that these rubbers can be manufactured with variable friction. The friction pads are manufactured using a manufacturing process called moulding. The compression moulding process is used to make the friction pad. The silicone rubber is partially covered by a non-friction material to make it anisotropic in nature to provide variable friction. These friction pads are connected to ends of the flaps of robot as shown in the Fig.8. These friction pads produce friction based on the applied lateral force. The change in direction of applied force change the contact points of friction pads, which in turn produce variable friction. The robot can move forward and backward based on the variable friction produced by the friction pads.

4.2. Electrical circuit
The first prototype of this robot uses Arduino pro-mini as controller, it’s a microcontroller which is based on atmega328. It can operate on 3.3V and 5V and has clock speed up to 8MHz to 16MHz. It has 6 analogue pins which can be used to connect analogue sensors and have 14 digital input/output pins of which 6 are PWM and are used to control the speed of the servo. The actuator used is a serial smart servo having torque 17kg.cm, operate on 7.4V with servo accuracy of 0.24°. The operating frequency of both servo and microcontroller is different. Serial communication between servo and microcontroller are obtained using an intermediate communication circuit called TTL linker. The operating voltage of TTL linker is 5V. The servo is connected to the linker by connecting pins. The linker is interfaced with Arduino by using TX and RX pins of the linker and Arduino to obtain serial communication between Arduino and servo. The power supply for the robot is provided from external power source, maximum operating voltage for the robot is 7.5V, 2A. The TTL linker also act as a driver circuit for controlling the smart servo.

5. Robot Simulation and Control
The Robot uses a serial servo for the actuation of the flaps. These serial servos uses serial communication and control signals are passed through serial connectors. Initially a simulation is developed in Simulink using Matlab to study the relation between applied torque and resultant motion. The CAD model of the robot is imported to Matlab software and control schematic is drawn based on kinematic equations. Fig.10 shows the schematic block diagram for controlling the robot. A torque is applied to the servo based on the calculations Fig.11 shows the graph of motor torque vs time graph. The robot uses crawling for generating motion. Individual module uses two-anchor crawling and multiple modules connected together uses peristaltic crawling locomotion. Different gaits were developed to generate crawling locomotion and these gaits were programmed into different functions and loaded on to the controller. These generated functions loaded on to the controller are used for testing the robot in different terrains. Based on the function call different robots perform different crawling locomotion. A torque 2N-m was applied on to the linear servo to change angular position for inching forward. By changing the angles θ₁ and θ₂ a change in step size is obtained. The angles θ₁ and θ₂ are changed by changing the servo angles. Based on the change in angles a change in step size is calculated, the change in step size gives the distance moved by the robot.
6. Experiment, Testing and Results
The first prototype of the robot is manufactured and is tested under the laboratory conditions. Several experiments are conducted to validate the characteristics of the robot such as Origami, Modularity and re-configurability. The robot is also tested to validate search and rescue operation. In order to validate the crawling locomotion and search and rescue operation the robot is tested on dry and wet concrete surface. Search and rescue environment is created and an experiment was carried out in laboratory conditions.

6.0.1. Validation of characteristics of the robot
The robot has the characteristics of both modular and origami inspired robots. Multiple modules are created and features of modular robots are implemented and tested on the robot. The robots are able to connect, disconnect and re-connect to form various configurations, satisfying modular features of the robot. The features of origami are satisfied by verifying the overall thickness of the robot. Overall thickness of the robot without actuator is 6mm. The ability of the robot to change from 2D to 3D shape is also implemented and tested to prove characteristics of the robot.

6.0.2. Two-anchor crawling
The robot uses crawling as a form of locomotion. Each individual module uses Two-anchor crawling for locomotion. Two-anchor crawling is a form of locomotion mainly seen in inch worms. The flaps of the robot act as two anchor, the two flaps generate friction based on their movement to inch forward. The Fig.12 shows the two-anchor crawling of robot on dry concrete and the similar experiment was also conducted on wet concrete, based on their movement displacement-time graph was plotted as shown in the Fig.14.
6.0.3. Peristaltic crawling

The robots when connected in chain configuration uses peristaltic crawling locomotion. Peristaltic crawling is a form of crawling where periodic contraction of the body takes place to move forward. In this robot, three modules are connected in a chain configuration and in combination generated peristaltic crawling. The peristaltic crawling is carried out on dry and wet concrete, as shown in the Fig.13. The step size is calculated and displacement-time graph is plotted to validate the peristaltic crawling motion of the robot as shown in Fig.15.

7. Conclusions and Future Work

In this paper we present a new origami inspired crawling modular robot, having design inspired from origami and have the characteristics of modular robot. The ability of the robot to connect, disconnect and re-connect enabled to re-configure its shape and is able to form different configurations. The robot was also able to perform Two-anchor and peristaltic crawling individually and in snake configuration. In order to validate the crawling locomotion and mobility in unstructured environment the robot is tested on dry and wet concrete surface. Displacement-time graph is plotted for two-anchor and peristaltic crawling locomotion’s. Our future work include developing intelligent control for crawling using neural networks and reinforcement learning. Exploring various light weight material and actuator so that overall size and weight of the actuator can be reduced. We will also implement various sensors that are suitable in supporting search operation.

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