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Design of connector for self-reconfigurable modular serpentine sensing robot with quality function deployment

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DESIGN OF CONNECTOR FOR SELF-RECONFIGURABLE MODULAR SERPENTINE SENSING ROBOT WITH QUALITY FUNCTION DEPLOYMENT

by

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A project

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Engineering

in the program of

Mechanical Engineering

Toronto, Ontario, Canada, 2005

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DESIGN OF CONNECTOR FOR SELF-RECONFIGURABLE MODULAR SERPENTINE SENSING ROBOT WITH QUALITY FUNCTION DEPLOYMENT

ARUP ROY
Master of Engineering, 2005
Program of Mechanical Engineering, Ryerson University, Toronto

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Abstract

This study presents the concept, design, force and stress analysis of a connector, which helps in transmitting mechanical forces, power, and data from one module to another in self-reconfigurable modular robotic systems. The connector is the most important part of self-reconfigurable modular robotic systems to connect and disconnect the modules. This part needs to fulfill a wide range of requirements. The two important properties, latching and geometrical shape have been focused on for designing the connector. The connector includes male and female components. The male component has a target ball; the female has a cup shaped socket, a locking ball, and an alignment cone with teeth for connecting with the male component. Two methods, quality function deployment (QFD) and Pugh decision matrix have been used for optimizing this design. In addition, for designing the connector of a self-reconfigurable modular serpentine sensing robot, one particular area of application and one special configuration of a self-reconfigurable modular robot have been taken into consideration. Based on the results of this project, a guideline for improving and optimizing the dimensions and for analyzing different forces and stresses for designing of the connector is provided to make a good model.

Acknowledgements

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There are not enough words to express my gratitude to my father, mother, lovely wife, sister, brothers, children, and all the best friends. Their prayers, love, encouragement and supplication always accompanied me to face the hardness and difficulty. Finally, the author would like to express his deep feeling of joy to almighty God for the spirit and course to accomplish this project work during one of the crucial phases in his career.

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Nomenclature

Chain: A series of connected links

Delrin: A special types of material

Dynamically reconfigurable: The shape can be changed on-line

Homogeneous: Identical or uniform structure

IR: An infrared type sensor

Lattice: A network of crossed laths or bars

Module: A self-contained unit

Modular robots: These robots consist of several similar types of modules

Node: A knob

Reconfigurable: The shape and the size of the robot can be changed

Robot: Robots are an artificial entity physically interacting with real world

Segment: A section

Self-reconfigurable: The robot can change its own shape

Serpentine: Like a serpent

SMA: Shaped memory alloy

Taxonomy: The classification of things into groups based on similarities of design and function

Versatile: Turning readily from one occupation to another

Chapter 1

Introduction

There are various definitions of “Robot”. The meaning of “Robot” is worker. Karel Capek first used this word in 1921. The Robot Institute of America defines a robot as a programmable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks. The primary application area for a robot is still in the sphere of mass-production. Researchers are trying to move the application areas of robotic systems into areas beyond that of mass-production. The ‘real-world’ is a challenge for robotic systems, because they are unstructured, dynamic, and complex. Robotic systems may be introduced to manage dangerous, dirty, and dull jobs in real environments. The most useful applications are in the fields of search and rescue, mining, planetary exploration-space, underwater, medical and so on.

The evolution of robotic systems over the years can be classified into three generations. The first generation of robots is capable of doing repetitive work as programmed. The second generation of robots can switch from one repetitive motion to another, as they are equipped with sensory devices. It is the third, i.e., current generation of robots that have the intelligence to make decisions for self-reconfiguring into any shape to perform different types of tasks.

Self-reconfigurable robots are a new concept in this technology. The key concepts of these self-reconfigurable robots are their ability to change their configuration automatically, enabling them to adapt their shape to suit multiple and changing tasks. This type of robotic system has three main types of components a) body (module), b) actuator and, c) connector. The basic idea is to build a complicated system from a varying number of modules. It is also called a self-reconfigurable modular robot. This type of robot could be built from ten to hundreds, even millions of modules (Sengupta et al., 2004). In place of designing a new and different mechanical robot for a particular job, many copies (i.e., prototypes of one simple module) are built. Individual modules cannot do much work, but when connected together, they make a system that can do complicated tasks. In practice, self-reconfigurable modular robots can change their shape by moving their modules around to meet the demands of different working environments. Modules have different degrees of freedom and they can share their standard connection interfaces allowing them to attach and detach from one another. These make them capable of rearranging their positions and connections within the robot and transform the overall configuration.

The connector is a vital part of this kind of robotic system. Bad design of the connector will limit the capacity, versatility and robustness of a completely robotic system. The self-reconfigurable modular robotic system is the basic part of this study. There are different application areas with different configurations of these types of robotic systems. This project is limited to a particular application area, i.e., sensing, detecting, and identifying of objects, and considers a particular configuration, i.e., a serpentine type robotic system, because this system is flexible for specific movement and work. The connector is used for connecting modules and makes a complete self-reconfigurable modular serpentine sensing robot (refer to Fig 47).

This project focuses mainly on geometrical shape and latching to design a connector. These two are the most useful and important properties of the connector for transmitting mechanical forces, power, and data. The connector must be lightweight, strong and be able to align large offsets laterally, as well as rotationally.

This project report is organized into five chapters. Chapter 1 consists of an introduction. A brief picture of self-reconfigurable robots, descriptions of different types of connectors used in self-reconfigurable robots, application of self-reconfigurable robots, and special application in serpentine type robotic systems are presented in Chapter 2. Chapter 3 deals with the methodology used in the design concept. Chapter 4 gives the design and concept development of the final design of the connector for self-reconfigurable modular serpentine sensing robots. Chapter 5 presents the conclusion.

Chapter 2

Self-reconfigurable modular robots, their connectors, applications, and serpentine robots

2.1 Introduction

The hierarchies for the robotic systems are shown in Fig 1 and this hierarchy means subclasses of robotic systems. First, robots are an artificial entity physically interacting with real world. The modular robots consist of several similar types of modules. It is easy to maintain and repair. If any module breaks, it can be identified and replaced very quickly, but in the case of non-modular robots, it takes more time to replace the whole robot. In the case of reconfigurable modular robots, the modules are independent and to a high degree homogeneous. It can reconfigure into different shapes and sizes and increases its versatility. Dynamically reconfigurable modular robots can reconfigure at the time of run. Non-dynamically reconfigurable modular robot cannot reconfigure at the time of run. Designing of module and connector are the challenging task to detect detachments and attachments of modules at run-time and potentially to change behavior depending on the new configuration. Dynamically reconfigurable modular robots are divided into dynamically user-reconfigurable modular robots and self-reconfigurable modular robots. User-reconfigurable modular robots can change their shape as per the user guidance but self-reconfigurable modular robots can change their shape as per the requirement of the tasks.

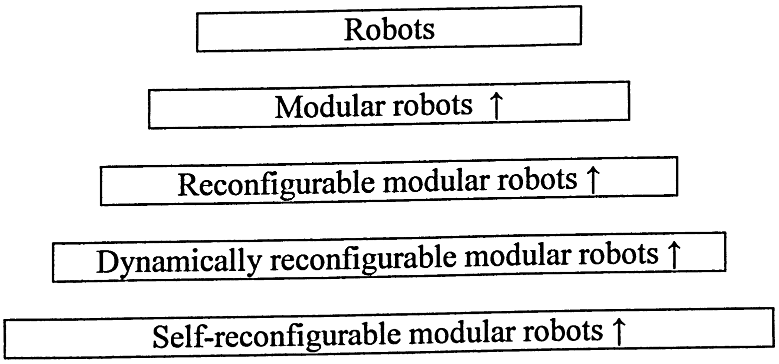


Fig 1: A taxonomy for modular robots (Stoy, K., 2004)

This chapter presents a brief overview of existing self-reconfigurable robots, their connectors, different applications of these robots and special application area of serpentine robot.

2.2 Self-reconfigurable modular robots

Self-reconfigurable modular robots satisfy the following criteria:

- modular-the robot is made of modules,
- reconfigurable- the size and shape of the robot can be changed,
- dynamically reconfigurable- the shape can be changed on-line, and
- self-reconfigurable- the robot can change its own shape.

There are two classifications of self-reconfigurable modular robots: Chain types, and Lattice types as per PARC (Palo alto research center, Palo alto, CA, 94304) and MEL (Manufacturing engineering laboratory, The national academics press) researchers (Stoy, K., 2004).

For example, chain type robots are polypod, polybot and conro. A chain type self-reconfigurable modular robot consists of branching modules, chain modules, and end modules. A chain type self-reconfiguration can be achieved by (1) creating branching modules by connecting one end of the module on the chain, (2) creating chain modules by connecting two end modules or by removing modules from branching modules, (3) creating end modules by splitting a chain. These sequences of activities complete the reconfiguration.

Examples of lattice type robots are metamorphic, crystalline, fractum, micro, RIKAN vertical, telecube, MEL 3D, robotic molecule, MTRAN, and I-cubes. Lattice type self-reconfigurable modular robots reconfigure by moving the modules around the lattice with the help of neighboring modules (Stoy, K., 2004).

2.2.1 Chain type systems

Chain type systems are classified based on their increasing complexity.

i) Polypod

Mark Yim (Yim, M., 1993) first introduced Polypod in 1993 as a dynamic modular reconfigurable task oriented robot. Polypod is composed two basic modules, the segment and the node (refer to Fig 2). The former is a 10 bar linkage with 2-DOF and two connection points while the node is a cube with six connection points on each of its six faces. The cube carries the batteries. When the numbers of segments are attached end-to-end, snake-like legs form or when number segments are attached to nodes, many legged robot forms. A segment has a small DC motor, sensor, and an 8-bit microcomputer housed in the outer structure of the segments. The connection mechanism helps the modules to connect and disconnect the neighboring modules and transmit power and data. Since the connection plates are symmetric, they allow the segments to be attached to each other in the same plane as well as in perpendicular planes.

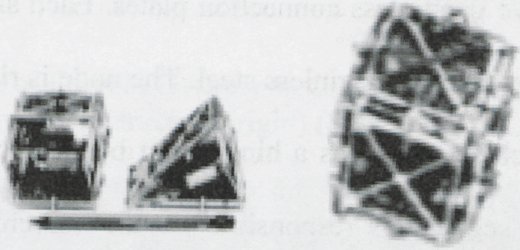


Fig 2: A Polypod segment module (left) & node module (right) (Yim, M., 1993)

ii) Polybot

It is an advanced version of Polypod. Polybot (Yim et al., 2000) is a modular self-reconfigurable robot system, which results in a large number of interchangeable modules and demonstrates locomotion on different terrain. The evolution of Polybot (Yim et al., 2001), (Zhang et al., 2002) over the last few years is as follows. Three generations (G_1, G_2, G_3) polypod are shown in the Fig 3, Fig 4, Fig 5 and Fig 6.

Generation I (G_1): The G_1 is manually reconfigurable (Yim et al., 2001), the module is cube shaped and is made of laser cut sheet of delrin. Each side of the module is square.

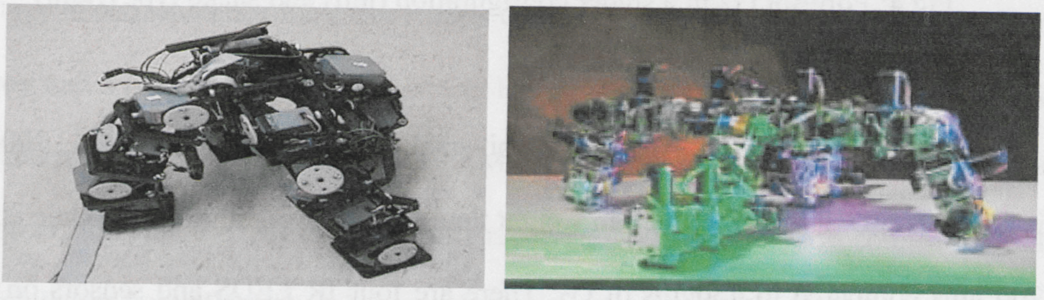


Fig 3: A Polybot G_1 with 16 modules in a four-legged spider configuration (Yim et al., 2001)

Generation II (G_2): The G_2 can automatically reconfigure. Its locking and unlocking features are fully automatic and much stronger than G_1. It is composed of two types of cube shaped modules called the segment and node. These homogenous, 1DOF modules have genderless connection plates. Each side of the cubic module is five cm and made of laser cut stainless steel. The node is rigid, having six connection plates, whereas each segment has a hinge joint between two genderless connection plates. This hinge segment is responsible for the movements of a robot. The two connection plates segments connect two other modules electrically and physically with a 4-way rotational symmetry. The connection takes place when four grooved pins enter four holes and are locked by a latching mechanism activated by a shape memory alloy. Once the modules are connected, power and information are transmitted from module to module. Two types of sensors, position sensors and proximity sensors are used in Polybot G_2 robots.

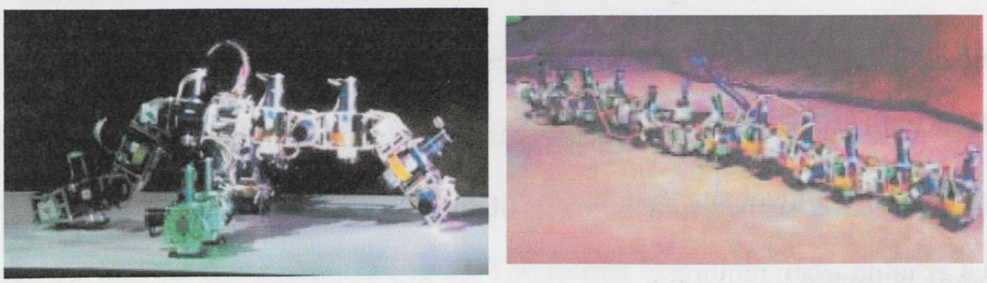


Fig 4: PolyBot G2 in a spider configuration (left) and snake type (right) (Yim et al., 2001)

Generation III (G_3): The G_3 is a bit smaller than G_2 (Sengupta et al., 2004). It is 5x5x4.5 cm. It is also lighten in weight than G_2. The weight of this module is only 200 gms compared to 450gms of G_2. There are four IR LEDS and sensors on each face for face-to-face docking and communication between the modules. Infrared emitters and detectors, mounted on the connection plate, help in docking.

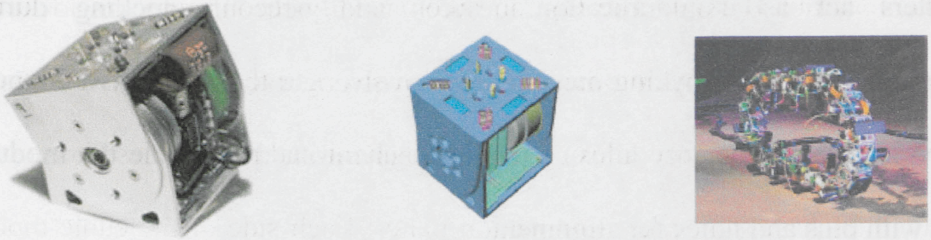


Fig 5: Early prototype of Polybot G_3 (left). A CAD image of Polybot G_2 (middle). A Polybot G_2 in a loop structure (right) (Sengupta et al., 2004).

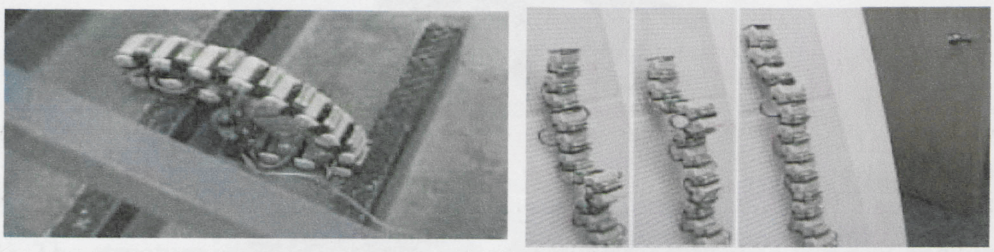


Fig 6: A loop configuration climbing stairs (left). A caterpillar locomotion climbing a vertical porous material(right) (Zhang et al., 2002).

iii) Conro Robots

Conro robots are self-contained, reconfigurable robots (Castano et al., 2000, Khoshnevis et al. 2001). They are composed of a delrin frame. These robots are designed in such a way so that they can support inter-robot reconfiguration. This means the merging of small robots to create a bigger one or splitting a large robot into smaller units when required.

Conro modules have three parts connected in a chain: an active connector, a body and a passive connector shown in Fig 7. Each conro module is a self-sufficient miniature robot that contains one STAMP II microcontroller, two batteries, and two motors, four pairs of IR transmitters / receivers and four docking connectors. Each module has two DOF for pitch (up and down) and yaws (right and left). The length of the module is 108 mm and it weighs around 115 gm, including the battery. IR transmitters act as communication devices and help in docking during a reconfiguration action. Docking mechanisms involve active and passive connectors, with a SMA (Shape memory alloy) latching mechanism, that enable the modules to connect with pins and holes for alignment.

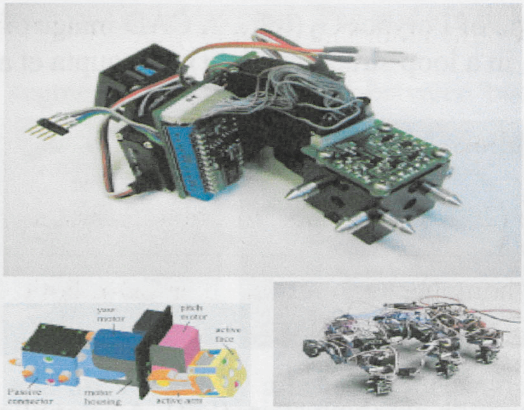


Fig 7: A close-up of a CONRO module (top). A CAD image of a CONRO module (left).A hexapod built from CONRO modules (right) (Castano et al., 2000)

2.2.2 Lattice type system

This system is classified from 2D to 3D by increasing complexity.

i) Metamorphic

A metamorphic robotic 2D system is composed of a number of independently controlled homogenous mechatronic modules (Chirikjian, 1994). It cans self-reconfigure without any outside help (refer to Fig 8). The relative locomotion of the modules results in change in morphology of the robotic structure. By connecting or disconnecting from the neighboring modules, a metamorphic robot can change its morphology and move from one place to another. Hence, it is a colony of connected modules acting as a single entity.

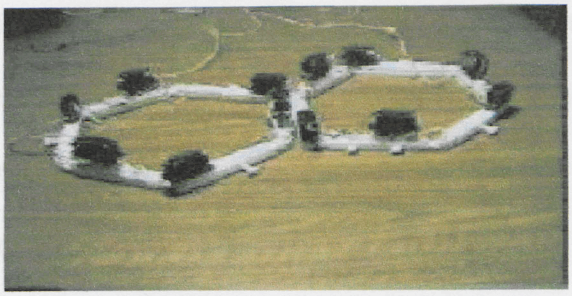


Fig 8: Two metamorphic robot modules (Chirikjian, 1994)

ii) Crystalline Robots

Rus and Vona (2001) first conceptualize the crystalline robot. They proposed a unique approach to homogenous unit-modular 2D-robotic system (Rus and Vona, 2001). The structure is composed of a cube with arms, which can contract and expand shown in Fig 9. The author named the module an atom and each connector a bond. Each unit has an expansion/contraction ratio of 2:1. To implement contraction and expansion of two-dimensional prototypes complementary "rack and pinion" mechanisms have been used. The connection is based on "channel and key" mechanism.

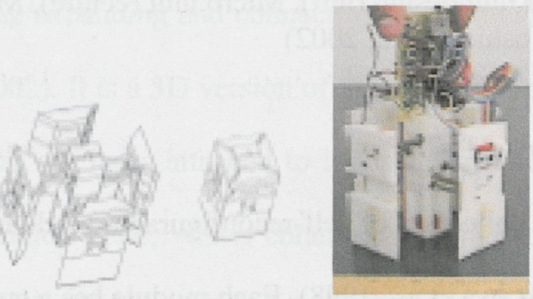


Fig 9: Mechanism (left), hardware of crystalline robot (right) (Rus and Vona, 2001)

iii) Fractum

Fractum is a lattice type 2D self-reconfigurable robot (Murata et al., 1994). It is made of homogeneous and reconfigurable units (refer to Fig 10). It can change its shape and function by reconfiguring the units.

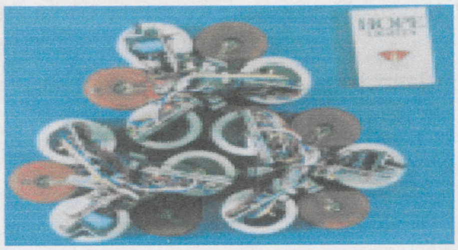


Fig 10: Three Fractum robots (Murata et al., 1994)

iv) Micro Unit

Micro is a self-reconfigurable, homogenous, modular microrobot (Yoshida et al., 2002). It is based on a new type of SMA torsion coil springs that can provide a higher power/weight ratio than electromagnetic motors shown in Fig 11. Hence, this lightweight module can generate torque and motion range sufficient for self-reconfiguration.

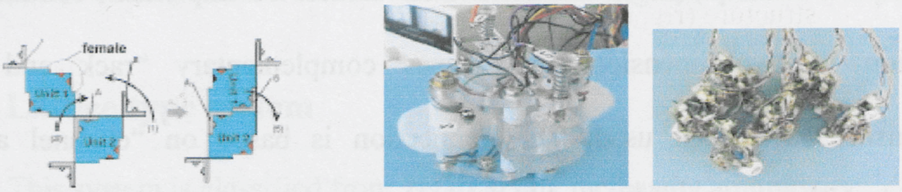


Fig 11: The Micro unit design (left). Micro unit (centre). Micro unit in a structure (right) (Yoshida et al., 2002)

v) RIKAN Vertical

RIKAN is a collection of self-reconfigurable modules and 2D systems in the vertical plane (Hosokawa et al., 1998). Each module has a cubic body made of plastic plates. The length of the cube is 90mm and its weight is 600gms. There is a pair of arms mounted on the opposite two faces of the cube (refer to Fig 12). The other four faces of the cube are equipped with permanent magnetic sheets for static bonding with another module. Modules have two degrees of freedom, one to control the extension/extraction of the arm, and one to rotate the arm. Arms have two degrees of freedom for rotation and sliding (extension and sliding). Arms contract when they make bond with arms of another body and expand when they disconnect. A 'lock-key' mechanism performs the arm bonding. For static bonding between the modules, magnetic sheets exhibit sufficient strength (tensile strength 3.3 kPa and shearing strength 4.8 kPa) to have a strong magnetic bond.

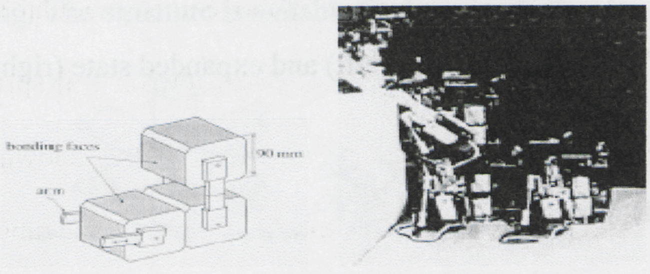


Fig 12: RIKEN Vertical modules (left). RIKAN Vertical modules in stair-structure (right) (Hosokawa et al., 1998)

vi) Telecube

A self-reconfigurable modular robot uses telescopic or prismatic degrees of freedom for contracting/expanding and connecting / disconnecting other neighboring modules (Suh et al. 2002). It is a 3D version of the crystalline robot shown in Fig 13. Each cubic module has six faces attached to independent linear actuators. On each face, there is a connection plate, which connects the other modules by latching a mechanism and transmits power and information. The locking and unlocking are low coupling and uncoupling forces. The module has six prismatic degrees of freedom. Each face of the module is a square of less than 6 cm and module weighs less than 30 gms. At the heart of the module, there is a motor core, which is made of Ertalyte, which holds the brushless DC gear motor. Six connection plates are attached to this core.

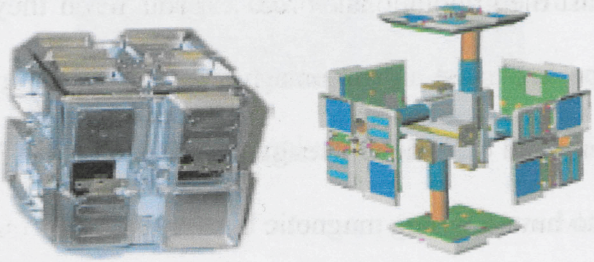


Fig 13: The Telecube casing (left) and expanded state (right) (Suh et al., 2002)

vii) 3-D Robots

Murata et al. (1998) have conceptualized the 3-D self-reconfigurable structure. The basic geometry of 3-D is based on regular hexagon. 3-D reconfigurable structure consists of homogenous units. At the centre of the each unit, there is a cube. Six sides of the cube hold six connecting arms (refer to Fig 14 and Fig 15). Any unit can connect or disconnect to another unit by its arm's automatic connecting mechanisms. Since each unit can rotate a connecting arm, an independently arbitrary unit structure can be formed by connecting or disconnecting other units. Twelve DOF is required for each unit six for rotation of arms and six for connecting or disconnecting of arms. Connecting mechanism is based on "key and key hole" relationship. Connecting mechanisms consist of a connection hand, a connection head and a connection cuff.

A movement of the 3-D structure takes place when two units of the structure play the role of a pivot. First, one unit becomes the pivot and repositions the partner on the other side and then the second unit acts as a pivot and repeats the action of the first unit. To accomplish the movement relative positioning among the units is very important. Each unit must have high power/weight ratio to lift up another unit of the same weight against the gravitational force. For rotation of the arms, worm gear and wheel combination are used. Each unit has an on-board microprocessor, torque transmission system, and communication system.

Another advantage of this structure is that different combinations of the units can construct anything. The structure is suitable for large and complex artifacts.

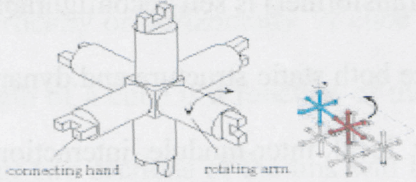


Fig 14: The MEL 3D unit (Murata et al., 1998)

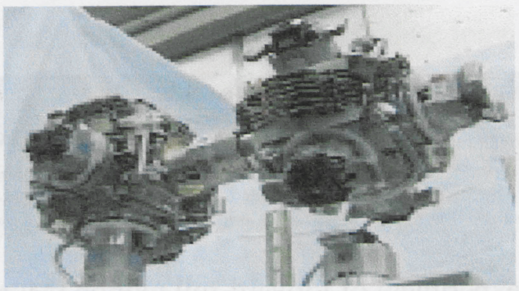


Fig 15: A Picture of two MEL 3D units (Murata et al., 1998)

viii) Molecule

This robotic system consists of small robotic modules called molecules, which are capable of self-reconfiguration in three dimensions (Kotay et al. 1998, Kotay and Rus, 1998). Each molecule consists of two atoms and a rigid connection bond shown in Fig 16. The size of each atom is 4 inches and weight of a module is 1.4 kg.

Fig 16: Molecule robotic modules (left). A robotic molecule structure (centre). A structure with robotic molecule hardware (right) (Kotay et al., 1998)

ix) MTRAN

MTRAN (Modular Transformer) is self-reconfigurable, homogenous modular robotic system that can realize both static structure and dynamic motion and can self-assemble and self-repair by local inter-module interactions (Murata et al.2000). There are mainly two types of motions, the global cluster movements called 'flow' and atomic motion for local reconfiguration called 'motion scheme' shown in Fig 17 and Fig 18.

Fig 17: The experiment of forward-roll motion (Murata et al., 2000)

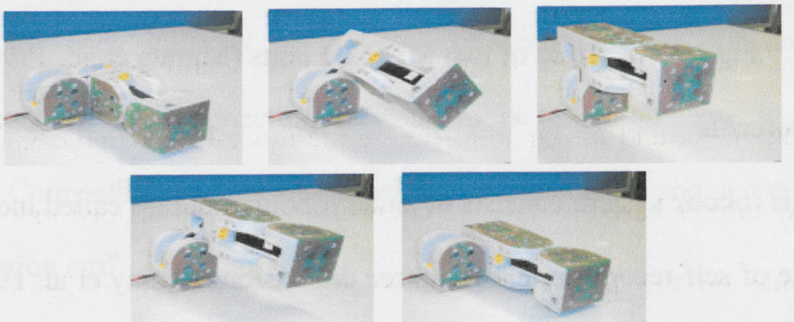


Fig 18: The experiment of mode conversion (Murata et al., 2000)

x) I-Cube

I- cube is a modular self-reconfigurable robotic system composed of two basic independent parts: links and cubes (Unsal et al., 2000a, 2000b). Links perform the reconfiguration jobs by connecting and disconnecting the cubes (refer to Fig19 and Fig 20). Reconfiguration of the structure takes place when the links move from one face to another face of a cube, or from one cube to another cube. A link can rotate or translate a cube vertically or horizontally. A cube sometimes acts as a pivot for a moving link. The length of a cube is a function of the size of a cube. If the size of a cube is r then length of two sections of the link will be r each and other two sections will be r/2 each. Three rotational degrees of freedom are provided by three joints of a link. These three joints, having worm gear mechanism driven by small servos, located at the middle and end segments of the link. The middle joint can rotate 270^0 whereas the two end joints are capable of rotating 360^0. Gear mechanism multiplies the torque provided by the servo at 1:40 ratio. This system provides an energy efficient actuation.

There are six connectors on the six faces of a cube. The size of a cube is eight cm. In each cube, there are on-board batteries, microprocessors and sensors for transmitting power and information among the modules. The attachment mechanism of link and cube is based on passive connection. A cross-shaped link connector first enters inside on the face of the cube and then rotates to its locked position. Connection mechanism also includes a SMA wire and a spring to actuate latch to complete the locking. I-cube is a feasible, energy-efficient and task-oriented robotic system.

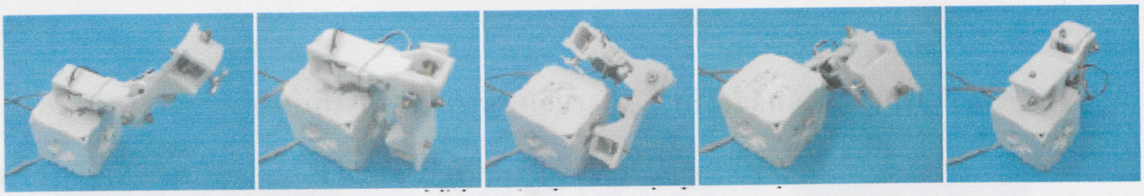


Fig 19: A link moving from one face to another (Unsal et al., 2000a)

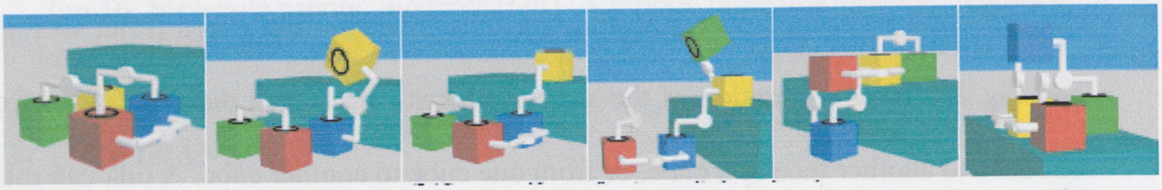


Fig 20: A group of I-Cube modules self-reconfiguring to climb an obstacle (Unsal et al., 2000b)

2.3 Connectors used in Self-reconfigurable modular robots

i) Dragon Connector

The Dragon Connector is a strong, lightweight and genderless connector and able to self-align (Nilsson, 2002a, 2002b). There are three basic components of a Dragon connector: the guide, the shell and the latching spring. While the shell, a thin layer of the connector's diameter takes most of the load, the guide, shaped as two funnels and two mating cones, helps to align the connectors. Fig 21 shows the video sequence of docking process.

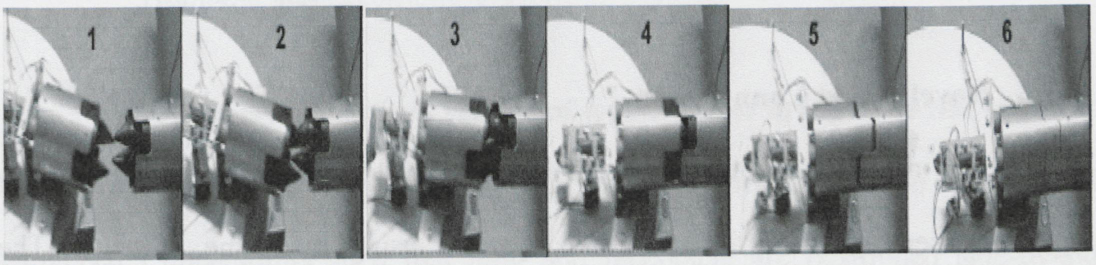


Fig 21: A video sequence of docking process of Dragon connector (Nilsson, 2002a)

ii) Telecube Connector

In the Telecube connector, the connection plate consists of permanent magnet devices with switching, IR sensors and transmitter, electrical contacts and printed circuit board. IR sensors, emitter pair and electrical contacts are placed in the centre of the plate (Suh et al. 2002).

The connection plate can accommodate up to 3 mm misalignment in any direction parallel to the plane. The magnetic forces are acting in between modules for coupling shown in Fig 22. Detaching is possible by shifting magnetic fluxes. The size of the magnet discs are 3.6 mm thick. In this magnetic system, the holding force is 160 gms, estimated holding force for each switching permanent magnet is 25 N.

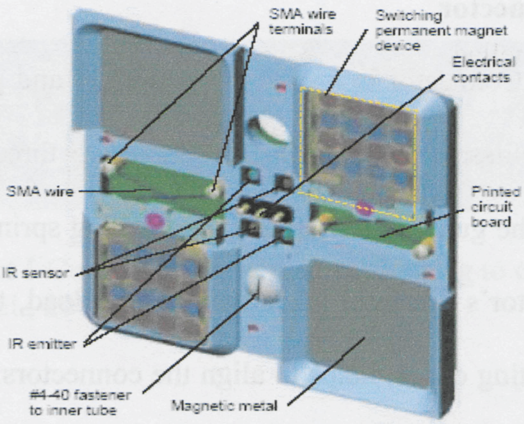


Fig 22: The Teletube connection plate (Suh et al., 2002)

iii) Novel Smart Connector

The modular robotic system is characterized by the reconfigurable, which ensures assembly of different robotic systems using the same modules. These modules contain Smart connectors equipped with actuators and sensors (Badescu and Mavroidis, 2001, 2003). The connectors must have mechanical and electrical connections that ensure the transmission of forces like torque, shear force and axial force to control modular engagement and disengagement and to send signals between neighboring modules. It also contains a self-latching device and allows fully automatic and manual operations as well as automatic emergency access from outside. The concept of novel smart connectors accommodates electrical connections of conductors as well as mechanical connections of components.

There are two types of connectors:

Type 1: It consists of a plug and a receptacle (refer to Fig 23). The former includes a central pin surrounded by a plurality of lamellae and the later, a pin housing corresponding to the central pin. The later also includes a number of lamellae for interconnection with plug lamellae and a SMA actuator for controlling movements of its lamellae.

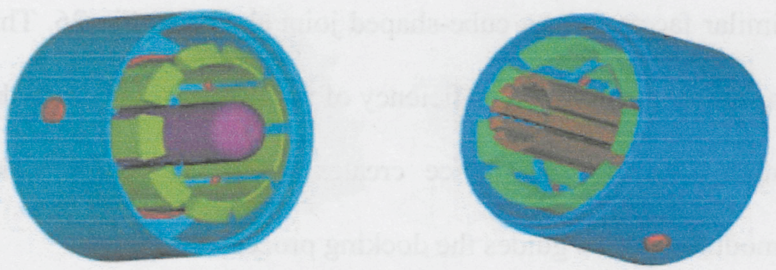


Fig 23: A Novel smart connector - Plug-male (Left), Receptacle- female(Right) (Badescu and Mavroidis, 2001)

Type 2: It is an improved version of type 1 shown in Fig 24 as this connector can also transmit torque in addition to axial force and shear force. The design of this Universal Connector is such that plug and receptacle are positioned side-by-side accommodating male and female components so that it can be interconnected with another identical connector.

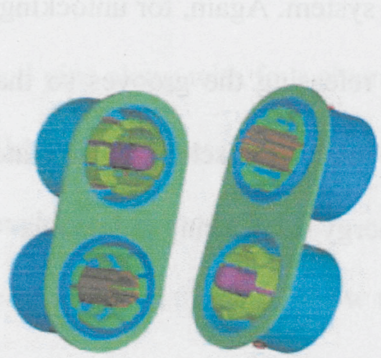


Fig 24: A Novel smart Universal connector (Badescu and Mavroidis, 2001)

iv) Conro Reconnectable Facets

The square-shaped facet of the conro connector contains two pins (two columns with cone shaped tips) and two holes at the four corners of the inner square at the centre of the surface, two pairs of sensing devices at the intermediate area and mounting apparatus at the corners of the facet (Khoshnevis et al., 2001) (refer to Fig 25). Five similar facets form a cube-shaped joint shown in Fig 26. This symmetrical design of the facets increases the efficiency of the joint by increasing the flexibility of reconfiguration. The sensing device creates a communication link between the connected modules. It also guides the docking process.

The number of possible docking alignments again depends on the pins and holes on a facet due to the symmetrical design of the facet. At the back of the facet, a thin S-shaped metal blade and a spring constitute the locking systems. With a spring motion, the blade can rotate around the centre. There are two ends of the blade (two curved tips are placed behind the docking holes). With the help of the spring, these two ends snap the groove of the pin when the pins slide entirely into the holes and this completes the locking system. Again, for unlocking, the ends of the blades can be replaced by a SMA wire releasing the grooves so that the pins can get out of the holes. This type of blade locking mechanism activated by a SMA wire is energy efficient as it consumes energy only during unlocking.

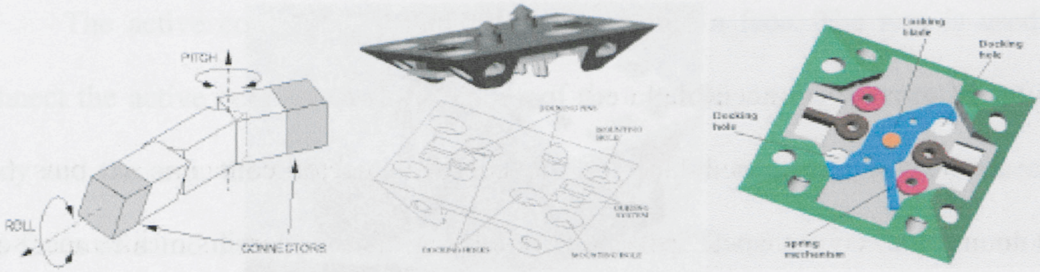


Fig 25: A Conro module (left). A Conro reconnectable facet (centre). The latching mechanism in Conro facet (right) (Khoshnevis et al., 2001)

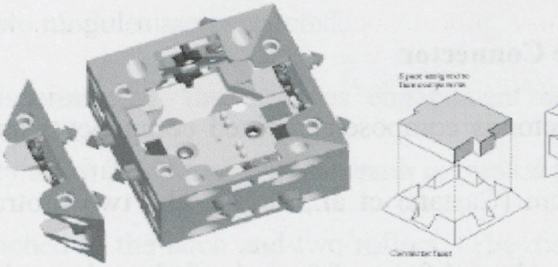


Fig 26: The integrated joint with five facets (left). Facets and the inner empty space (right) (Khoshnevis et al., 2001)

v) Polybot Connector

In this connector, two connection plates are used in each module (Yim, et al., 2000).The functions of these connection plates are to connect two modules physically and electrically. It also helps in transmitting both information and power from one module to another.

There are four grooved pins along with four chamfered holes on a connection plate shown in Fig 27. An SMA actuator rotates a latching plate that catches the four grooves in the pins from a mating connection plate. Two photo-diodes and 4 LED's on each connection plate are so arranged that they allow to determine relative 6 DOF position and orientation of a mating plug and thus helps in the closed loop docking of two modules and their connection plates. Two connection plates can be attached and detached through latch actuation, which enables self-reconfiguration.

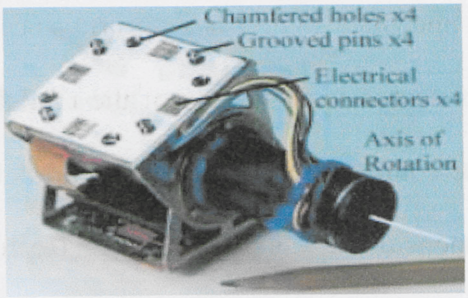


Fig 27: A connection plate with 4-pins, 4-mating chamfered holes and 4-electrical connector sets (Yim et al., 2000)

vi) Passive and Active Connector

The passive connector is composed of fixed components and shaped like a cube with a side of 2.54cm (Castano et al., 2000). The two protruding aluminum cylindrical pins on the three lateral faces of the cube fit into the sockets of the active connector of another module. The lateral groove of the pins allows the active connector to anchor the passive connector shown in Fig 28. A tongue on the fourth face of the cube fits onto a fork and allows connecting the module, which is on the yaw axis. This connector can rotate at around 60^0 in the both right and left directions. The hollow of the frame of the passive connector holds the battery, other infrared connectors and to keep the battery in place there is a latch at the bottom of the cube.

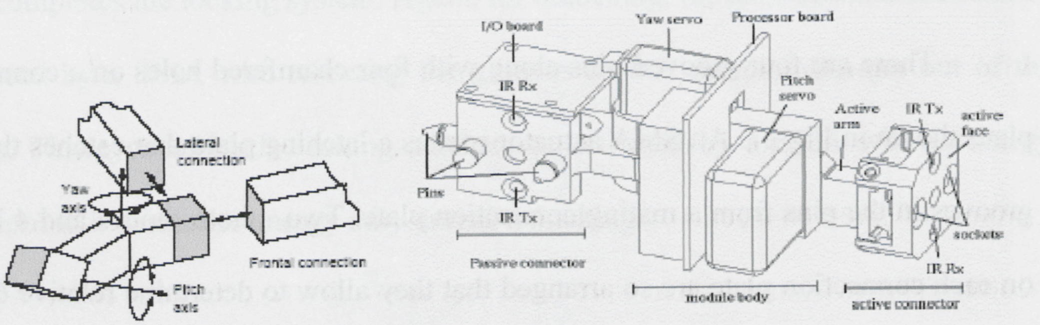


Fig 28: The basic shape of a Conro module (left). Parts of the Conro module (right) (Castano et al., 2000)

The active connector (15gms) has an arm and a face. The arm is used to connect the active connector and the body of the module. At the intersection of the body and the arm, the connector can rotate about a pitch axis. The active connector has faces of same dimension of the passive connector. There are two sockets on the face to receive the pins of passive connectors. As the pins slide fully into the sockets, the engagement latch rotates in a direction perpendicular to the trajectory of the pin and thus the two modules are connected.

For disconnecting, the modules engagement latch can be rotated using a shape- memory alloy (SMA) wire whose path is created between a fixed binding post, a cylinder attached to the latch and two rollers. The disconnecting process starts by contracting the SMA wire that helps the cylinder rotate clockwise against a spring. This initiates the rotation of both engagement and disengagement (a plate with two holes) latch. The engagement latch helps the pins to get out of the sockets for a fraction of a second and the disengagement latch pushes the dome-shaped head of the pins to a distance, which is enough to guarantee that when SMA is relaxed pins are not again inserted into the sockets and complete unlocking process.

vii) I-cube Connector

The connector is cross-shaped. Each face of I-cube is embedded with four groups of three connection points for four possible link orientations (Khosla et al. 2000). The twist-and-lock connection mechanism is used for the connector. The connector enters the cube faceplate and then rotates to its lock position inside an opening on the cube faceplate. Once the connector is in locked position, a sliding latch rotates to stop the connectors from turning back. A 14 cm wire pulls to rotate the latch and a torsion spring pushes it to its locked position (refer to Fig 29 and Fig 30). There is a 3-point electrical connection protruding away from the shaft. It helps to provide necessary power and serial communications. The inner most connection point on the face of I-cube is used for power transmission whereas the points on the outer side are used for serial communications.

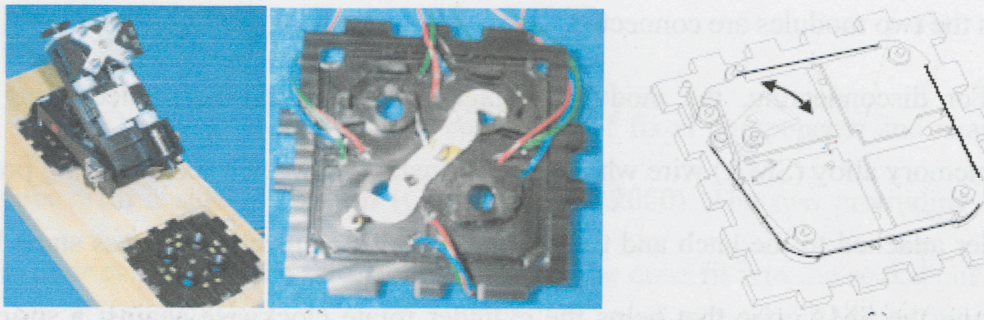


Fig 29: A 4-pegs with latch at the center of the faceplate (left). The twist-and-lock mechanism with sliding latch (right) (Khosla et al.,2000)

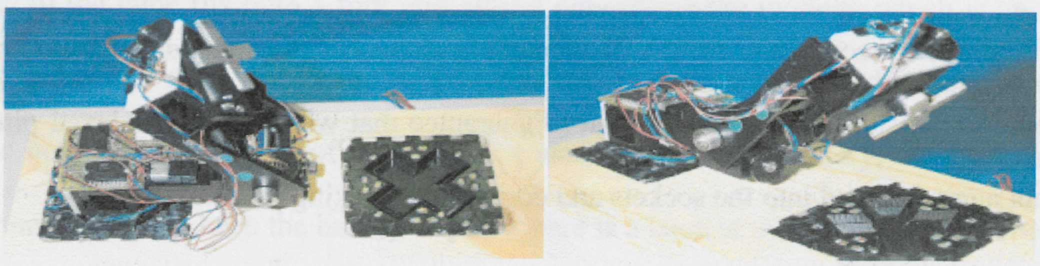


Fig 30: A link approaching the faceplate (Khosla et al., 2000)

viii) MTRAN Connector

In this connector, module consists of two semi-cylindrical parts and is made of delrin. Each semi-cylindrical part is 6 cm cube. These two cubes are connected by a link in which a servomotor is embedded. This servomotor enables the semi-cylindrical parts to rotate by 180 degree. Each semi-cylindrical part has three faces that can connect and disconnect other modules by magnets and SMA actuators embedded in each face shown in Fig 31. For power supply, serial communication from module-to-module, connecting faces also have electrodes. There is an on-board PIC microprocessor in each module that controls servomotors and SMA actuators. Each module weighs around 400 gms.

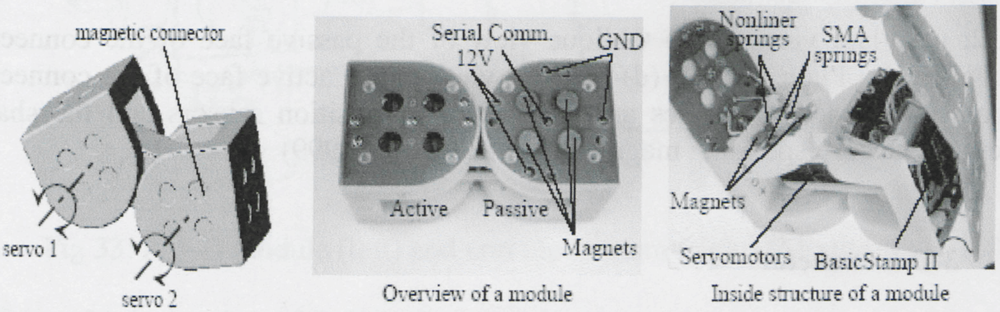


Fig 31: A MTRAN robotic module (left), overview of a module (centre), inside structure of the module (right) (Murata,et al., 2000)

ix) Channel and Key Mechanisms Connector

Channel and Key is the underline concept of this connection mechanism (Rus and Vona 1999). Its active face has a gear-motor whereas its passive face contains a deep horizontal channel shown in Fig 32. A key is attached to the gear motor and pockets are built into the upper and lower inside of the horizontal channel. Now, from one angle key can slide into the horizontal channel of the passive face without any obstruction to make the connector free, and the connector is bonded when key is rotated and hence extends into the pockets of the passive face of the connector. Hall-effect sensors determine the position of connector key.

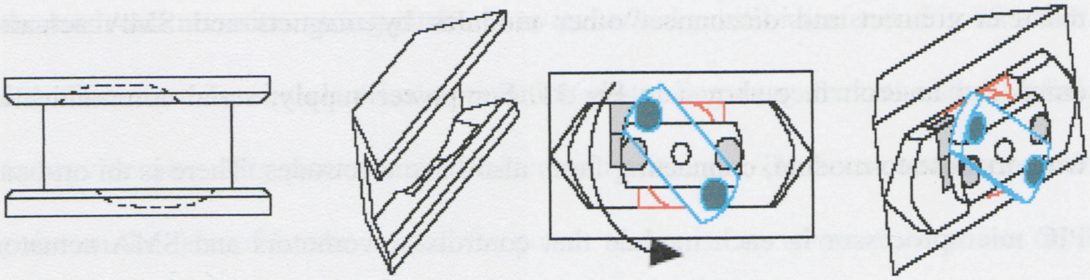


Fig 32: (a) Plain view & (b) Oblique view of the passive face of the connection mechanism. (c) Plain view & (d) Oblique view of the active face of the connection mechanism. Shaded rectangles are the hall-effect position sensors and the shaded circles are the corresponding magnets (Rus and Vona, 1999)

x) 3-D Connector

This three-dimensional structure is made of identical units (Murata, *et al.* 1998). There is a base cube at the centre of the structure having six connecting arms for connecting neighboring units (refer to Fig 33). The base cube is called carrier. When all six arms connect the neighboring units, a cubic lattice forms. An arm can carry a neighbor unit from one node of the lattice to another having 90^0 rotations. The neighboring units are called passengers. Each arm can connect or disconnect its neighboring units mechanically. Hence, the structure can have different configurations by rotating arms and/or changing connections with the passengers. The unit on which the carrier stands is called support. The connection mechanism is comprised of a pair of fingers, a head, an electromagnetic clutch and a cuff. Head of the arm is rectangular and prismatic shaped. It has two V-shaped grooves where the fingers of another unit get fit in. Before the connecting mechanism starts, the relative angel of two arms of carrier and passenger respectively are adjusted. The electromagnetic clutch enables the cuff to slide along a screw shaft that is connected to the centre transmission shafts. When two cuffs slide up to the end and touch each other, the fingers are pushed and fit in the grooves of the partners arm. Thus, the connection mechanism completes.

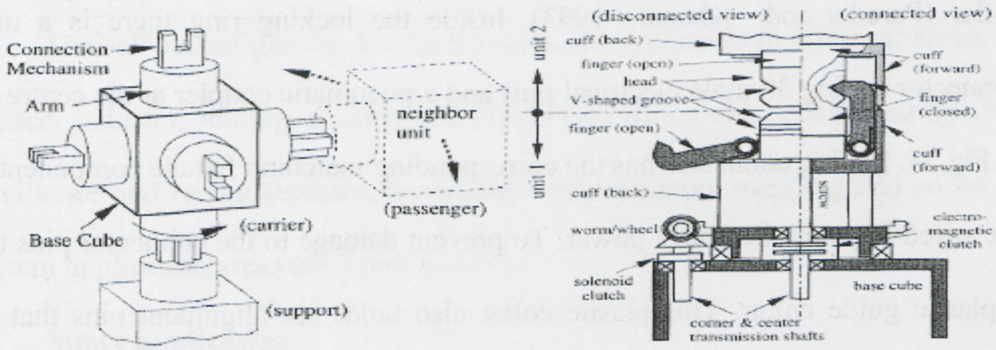
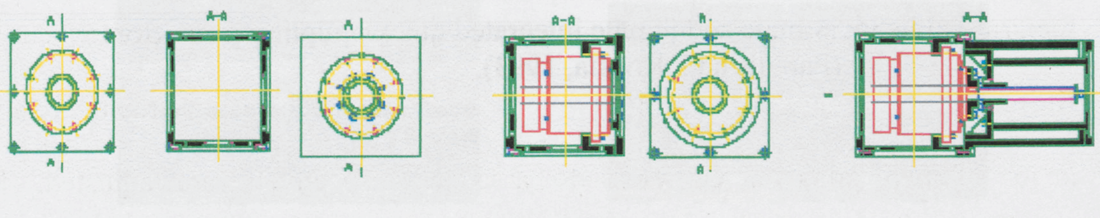


Fig 33: A 3-D module (left) and arm mechanism (right) (Murata et al., 1998)

xi) Link and Joint Module Connector

There are two categories of modules: Link modules and Joint modules (Chen and Yang 1996). Modules are made of cubic units, having connecting sockets on the faces, joined based on building block principle. The position of two connecting modules can be re-oriented by joining them through different connecting sockets. Again, Joint modules are of three types: Revolute joint, Prismatic joint and Virtual joint (refer to Fig 34). When the connector is fasten to the rotating socket of the revolute joint it is known as Revolute joint connector and when it is fasten to the translating socket of the prismatic joint, it is known as Prismatic joint connector. The Virtual joint connector is one, which is fastening to two fixed sockets.



(a) (b) (c) (d) (e) (f)

Fig 34: (a) & (b) Link module. (c) & (d) Revolute joint module. (e) & (f) Prismatic joint module (Chan and Yang,1996)

xii) Integrated Quick-Coupling Connectors

Integrated quick-coupling connector consists of a locking ring and locking collar (Paredis and Khosla 1993). Inside the locking ring there is a modular connector having 30 male electrical pins and a pneumatic coupler at the centre shown in Fig 35. Mating connector has the corresponding matching female components. Pins are wired in parallel to carry power. To prevent damage to the connector pins there is a plastic guide collar. This plastic collar also holds six alignment pins that ensure eight different types of connection orientation. Connection between the modules can be achieved by simply rotating the fingers of the locking ring. This is done by turning the locking collar on the male end. The relative rotation between the locking collar and the locking ring results in ball-transfer mechanism between them, and then cam mechanism forces the fingers to grip the mating flanges.

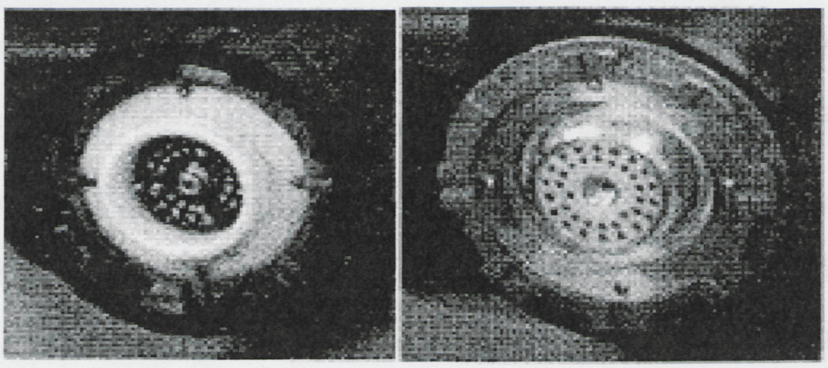


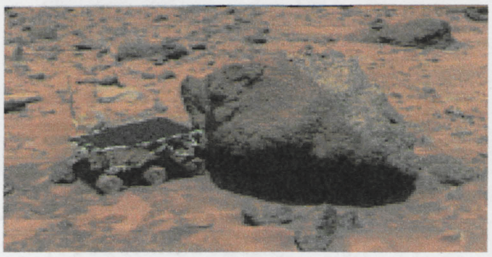
Fig 35: A male and female integrated quick-coupling connectors (Paredis and Khosla, 1993).

2.4 Applications of Self-reconfiguration modular robots

The self-reconfigurable modular robots are applicable in different areas, such as space, industry, mining, sensing and identifying living object in rescue operation, surveillance and reconnaissance, hazardous waste cleanup, mapping and so on. The different application areas are listed below:

i) Space application

The self-reconfigurable modular robot accomplishes a variety of tasks, such as building, digging, soil manipulation (front loader), and space station maintenance similar to submarine maintenance, instrument deployment transportation and exploration. The Figures 36 and 37 are taken from "Think for yourself, robot!", by Triesch, J.(2003).



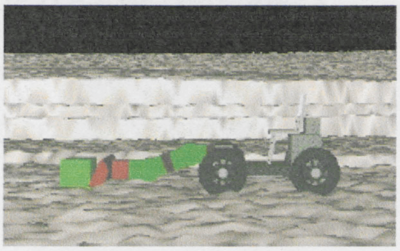
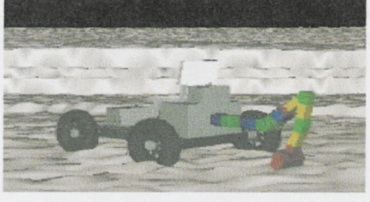


Fig 36: A space exploration (left). A soil manipulation- front loader (right)



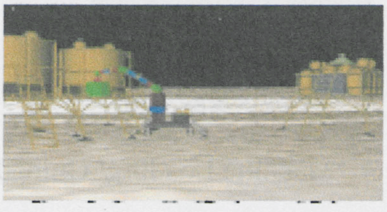


Fig 37: A sampler robot (left). A deployment-robot (right)

ii) Industry application

There are mainly two types of applications in shipbuilding industry such as dockwelder and spray painter shown in Fig 38.

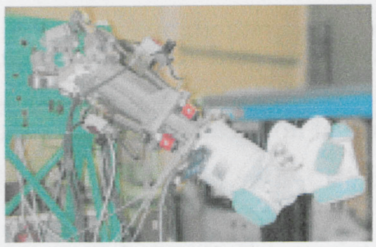


Fig 38: Dock welder manipulator consisting of four modules (left).
A spray painter- 10 dof manipulator (right) (Sorensen et al., 2004)

Different configurations used in factory application (Modular Reconfigurable Robot):

1. MRR-SCARA-4 DOF (refer to Fig 39)
2. MRR-ARTICULATE-6 DOF
3. MRR- GANTRY- 3,4,5,6 DOF
4. MRR-CUSTOM- 1-32 DOF

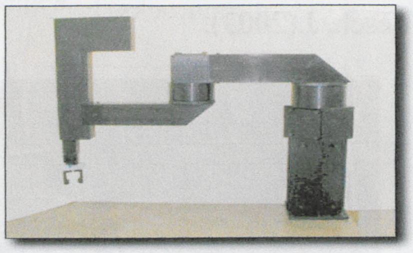


Fig 39: A SCARA Industrial robot (MRR online, 2004)

The different applications areas in industry are listed below:

1. Material Handling,
2. Mechanical Assembly,
3. Dispensing,
4. Machine Loading/ Unloading,
5. Process Applications,
6. Testing, sampling and inspections

iii) **Other applications**

Figure 40,41,42,43 and 44 show the different applications of reconfigurable robot. This author, takes these all Figures from, "Distributed intelligence in autonomous robotics", Parker, L.E. (2003).

Movies of polybot:

a) Stair climbing, b) Tricycle pedaling, c) Porous material climbing,

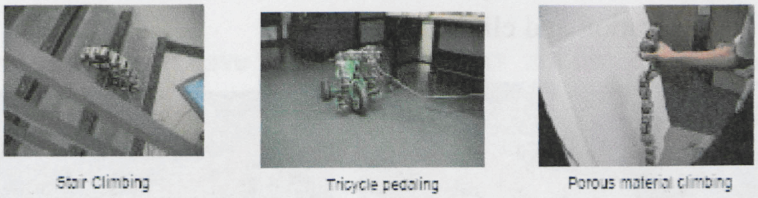


Fig 40: Movies of Polybot

Conro:

a) Rolling tracks, b) Caterpillars, c) Sidewinder snake,

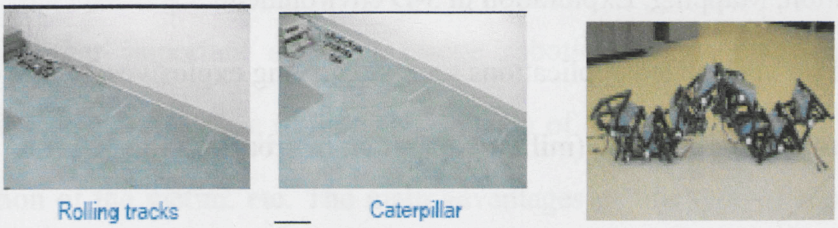


Fig 41: Conro movements

Mining and Surveillance and Reconnaissance

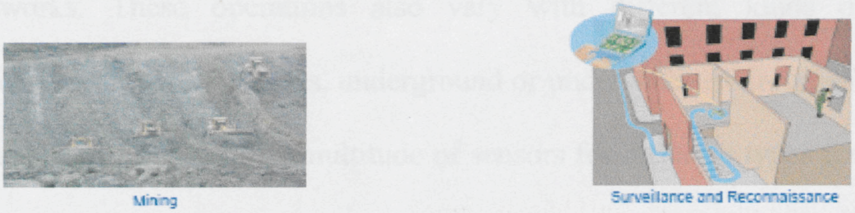


Fig 42: Mining operation (left). A surveillance and reconnaissance (right)

Hazardous waste cleanup and Adaptive Box pushing

Fig 43: Hazardous waste cleanup (left). Box pushing (right)

Navigation configuration and cliff

Fig 44: Navigation configuration and cliff

Localization, Mapping, Exploration in 3-D environment

Potential for specialized applications such as carrying explosives, bridge demolition and destroying barbed wire (military operation in urban terrain)

2.5 Self-reconfigurable modular serpentine sensing robot

2.5.1 Introduction

In our world, large numbers of people have died due to flawed rescue efforts. Lack of adequate equipment and a lack of self-reconfigurable modular serpentine sensing robots' timely response are the factors responsible for this (Erkman, I. et al., 2002). Many researchers have introduced robots suitable for disaster relief or dangerous zone work. 'Search and rescue' is a challenging area of research for robotic systems. Researchers are trying to develop mechatronic rescue tools and strategic planning tools for planning rescue operations. The robots are used in different hazardous and complex disaster environments. The main critical characteristics of these robotic systems are autonomy, high mobility, modularity and robustness. Other important areas of rescue robotic systems are detection and identification of living bodies, routing and clearing of debris in accessing the victim, transportation of the victim, etc. The main advantages of this type of robot are a) it can move in narrow places (flexible movement) and across rough surfaces, b) it can also move in a place with height differences, and c) it can change its configuration for specific works. These operations also vary with different kinds of disaster environments, such as urban areas, underground or underwater environments. Rescue robots must be equipped with a multitude of sensors for different types for detection and identification.

Hirose at the Tokyo Institute of Technology developed the first snake (serpentine) type robot (ACM III) (Hirose-1993). Different types of serpentine robots like ACM III, SHR, GMD, JPL, and SMA are now available in market shown in Fig 45.

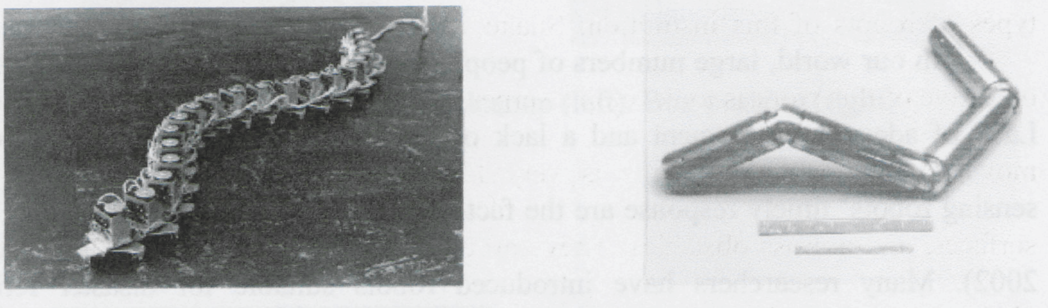


Fig 45: An ACM III (left). A JPL (right) (Hirose, 1993)

i) General serpentine robot (Dowling, K.J. - 1997)

General specifications of serpentine robot are- mass 1.32 kg, length 102 cm, diameter 6.5 cm, power 24.2 W, maximum total mechanical output 75 W.

ii) Spatial hyper redundant (SHR)

This robot is a serpentine type robot (Shammas et al, 2003). SHR is three-dimensional and has two DOF joint mechanisms. The joint is optimized for strength, compactness and it is strong enough to resist high loads developed by the robot's own weight and other dynamic loads generated by its spatial motions (refer to Fig 46).

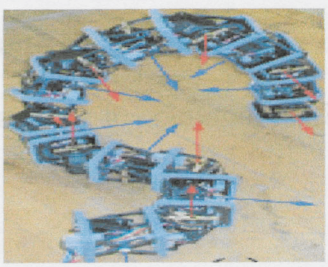


Fig 46: A SHR serpentine robot (Shammas et al, 2003)

iii) GMD Snake 2

GMD (German national research center for information technology, German) has developed this robot (GMD'S AIS, 1998). This is the latest one, i.e., called 'GMD Snake 2' serpentine robots shown in Fig 47. There are two versions of serpentine types of robots of this institution: Snake 1 (1996) and Snake 2 (1998). The main objective of this work is to develop a serpentine robot similar to biological snake. The movement of natural serpents is very flexible. Serpentine can move on rough surfaces, and a cross obstacles. They can creep into different areas, which are very difficult to arrive with any other type of movement. That means serpentine types of robot will be an ideal sensing system. The GMD Snake 2 serpentine robot consists of identical modules. A maximum 15 modules can be connected together by connector to form the complete serpentine. The electrical and mechanical design of GMD serpentine robot is as simple as possible to achieve an optimized ratio of its weight and the force it can apply. The specifications of GMD Snake 1 (1996) are length 200 cm, weight 3 kg, diameter 6 cm, average power consumption 15 Watt, and creeping speed 50 cm/min. Those of GMD Snake 2 (1998) are- length 90 cm, diameter 18 cm, weight 10 kg, power consumption 40 watt, and capacity of the battery 47 Wh. The new robot (GMD-2) can apply torque of more than 12 Nm to any joint and it can move at a speed of 0.1 m/sec (natural snake speed (maximum) 3 m/sec (Dowling, 1997).

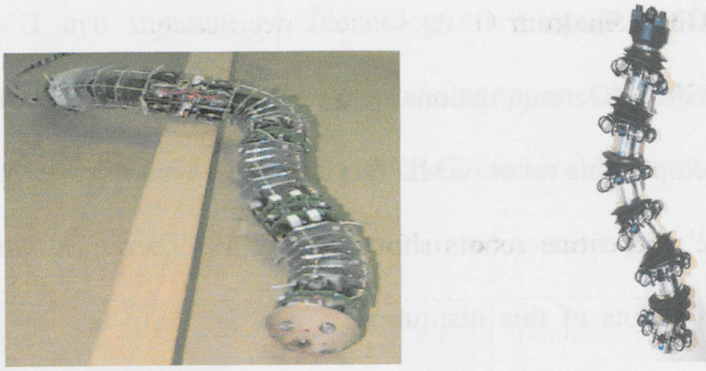


Fig 47: A GMD serpentine robot (GMD'S AIS, 1998)

iv) Super-Mechano Anaconda (SMA)

Yamakita el at., 2003, developed this serpentine robot (refer to Fig 48). The parameters of this robot are length 1.9 m, weight 10.5 kg, number of link 19, length of link 0.08 m, maximum joint torque 19.1 Nm, maximum joint rotation velocity 0.7 rad/sec.

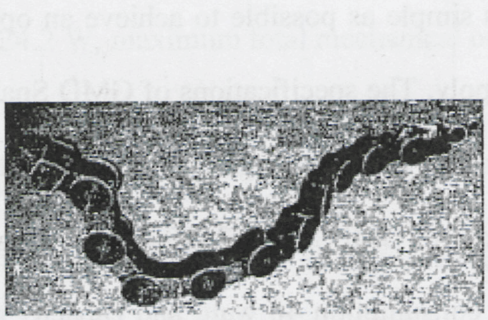


Fig 48: A SMA serpentine robot (Yamakita el at., 2003)

The above specifications of different types of serpentine robots are summarized and developed Table 1. The table shows the different types of serpentine robots in the columns and their specifications in the rows. The 'Target values' of this project, are listed in the last column of this table, based on these specifications. This study is focused on a particular configuration and a particular application area, i.e., self-reconfigurable modular serpentine sensing robot to limit the study. This project concept is very near to the GMD type serpentine robot. Therefore, most of the target values are taken from GMD snake2 specifications. The G3 type module has been considered.

Table 1: Specifications of different types Serpentine (Snake) robots

SPECIFICA-TIONS	GENERAL	SAR	GMD2	GMD1	SMA	SR2	CHINA2	ACM R3-21	ETR	TARGET VALUE
Total Length (cm)	102	xx	90	200	190	280	120	200	xx	90
Diameter(cm)	6.5	xx	18	6	xx	xx	6	xx	xx	Square
Weight (kgs)	1.48	xx	10	3	10.5	20	1.8	12.1	xx	3
Speed (m/s)	xx	50^0/s	0.1	50 cm/ min	0.7 rad/s	0.5	0.33 20m/m	40 cm/s	xx	0.1
Lifting capacity (number)	xx	05	3.8 kg H+ M(2)	xx	xx	xx	xx	xx	6	15
No. of modules	10	10	5+head+tail	15	19	20	xx	20	xx	15
Size of modules	L= 10.2 cm	82x82x67 mm	xx	xx	L= 8 cm	L= 14 cm	xx	1755 x 110x 110 mm	xx	50x 50x 45 cm
Wt. of modules	xx	300 gm	H=0.8 kg T=1.75 kg M=1.5	xx	xx	1051 gms	xx	xx	xx	200 gms

			kg							
Rotational angle	xx	$\pm 60^0$	xx	xx	$\pm 60^0$ (H) $\pm 90^0$ (V)	xx	xx	$\pm 60^0$	xx	$\pm 60^0$
Battery capacity	xx	xx	47 wh	xx	xx	xx	xx	xx	xx	47 wh
Current	9.5 mA @ 6 VDC	xx	xx	xx	xx	xx	xx	xx	xx	12 A
Power	24.2 watt (output), 75 watt (input).	xx	40 w plan Motion, lifting	15 w	xx	xx	xx	xx	xx	40 w
Torque	xx	20 kgf -cm	12 N-m	xx	19.1 Nm	xx	xx	19.1 Nm	4.5 Nm	12 Nm
Force-Axial	xx	xx	xx	xx	xx	xx	xx	xx	300 N	300 N
Bending	xx	xx	xx	xx	xx	xx	xx	xx	xx	600 N
Shearing	xx	xx	xx	xx	xx	xx	xx	xx	xx	500 N
Twisting	xx	xx	xx	xx	xx	xx	xx	xx	xx	500 N

SAR = Search and Rescue (Erkmen, I. et al, 2002), SMA= Super Mechano Anaconda, SHR= Spatial Hyper Redundant, ETR= Elephant tongue robot (Wolf, A. et al 2003), GMD= GMD institute. SR= Serpentine Robot, Speed of natural snake= 3 m/s (Dowling, K.J.). Max. Length of Snake robot= 1.6 m (64 inch), Speed= 6.6 km/hr (4 mph), Total number of modules= 32 general (max= 180-200) (Talon robot, Miller).

Chapter 3

Overview of design methodology for this project

3.1 Introduction

The following two methods are used for designing of a connector for a self-reconfigurable modular serpentine sensing robot: a) Quality Function Deployment (QFD) method, and b) Concept development by Pugh decision matrix method. In this chapter, these two methods are described in detail with their different steps. The QFD and Pugh decision matrix methods are applied in the chapter 4 for making a decision and finalizing the concept.

3.2 Quality Function Deployment

Yoji Akao is the father of Quality Function Deployment (Lowe, A.J. et al., 2001). He first implemented this method at the Mitsubishi heavy industries at Kobe shipyard in 1972. The rest of the world became aware of the usefulness of this method by reports of the achievements made by M/s Toyota through its application between 1977 and 1984. This system reduces 61% of the product development costs. Yoji Akao defined QFD as "**a method for developing a design quality aimed at satisfying the customer and then translating the customer's demands into design targets and major quality assurance points to be used throughout the production phase**".

The main objective of QFD is to fulfill customer needs by satisfying their actual requirements (called 'voice of customer'). QFD involves various functional departments like marketing, design engineering, quality assurance department, manufacturing engineering, test engineering, finance, and so on, for product development. It is teamwork and uses a comprehensive matrix for documenting information, perceptions and decisions. This matrix is commonly known as 'House of Quality'. In the QFD method, three management and planning tools are used in addition to the 'House of Quality'.

1. Affinity diagram
2. Pair-wise comparison (Analytic hierarchy process-Saaty, 2000)
3. Matrices and tables

i) The House of Quality

The product development team first uses the House of Quality to initiate a QFD method. This matrix is a powerful tool and it helps to convert the customer requirements into technical requirements in order to meet those requirements. The general format of the 'House of Quality' is made of eight major steps.

ii) Steps of the House of Quality

Step 1: List of Customer requirements ('Voice of the customer')

The starting point of QFD method is to determine what product will be analyzed during the process and to identify the customers. The team then collects information from customers on their needs of the particular product and customer expectations from that product. Different sources of information like customer interview, surveys, observations, contacts, suggestions, and feed back of both current customers as well as potential customers must be taken into consideration. The objective of the House of Quality is to design or modify the design of a product in a way that meets customer expectations. After that, customer needs and expectations are combined to make a customer requirement. A structured list of requirements derived from customer, is known as 'Voice of the customer'.

Step 2: Regulatory requirements

The customers may not know all product or service requirements. Therefore, the team must document requirements that are dictated by regulatory standards that the product must adhere to.

Step 3: Customer importance rating

After determining the customer requirements by the above methods, the collected data are summarized and documented by different techniques such as ranking, rating, and pair-wise comparison to determine the relative importance of customer requirements. Customer requirements are prioritized by using 1 to 5 (or 1 to 9) rating by ranking technique or pair-wise comparison technique. This study is used pair-wise comparison technique (Saaty, 2000). In this technique, common numerical values are used from 1 to 9, with 2, 4, 6, and 8 as intermediate values whereas 1, 3, 5, 7 and 9 for expressing the preferences between requirements (options) as equally, moderately, strongly, very strongly, and extremely preferred. Each pair-wise comparison represents the relative importance of the compared requirements. Applying Saaty's eigenvector method to these compared values, weighted estimates are calculated for each pair-wise comparison matrix.

Pair-wise comparison method (Saaty, 2000)

A pair-wise matrix is used to establish the relationship between different requirements based on their importance. The preferences are quantified by using a nine-point scale. The meaning of each scale measurement is explained in Table 2. The pair-wise comparisons are obtained in terms of how much element X is more important than element Y.

Table 2: The Fundamental Scale (Saaty, 2000)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	An activity is strongly favored and its dominance demonstrated in practice
7	Very strong importance	The evidence favoring one activity over another is of the highest possible order of affirmation
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocal of above	If activity i has one of the above non zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.	

The next step is to develop the normalized matrix. Each number (each cell) in a column of the base criteria matrix is divided by its column sum. The average of each row is called 'average weight' for respective requirements. The average weight of each row is multiplied by the pair-wise comparison (base criteria) matrix and formed a new matrix is called 'weighted sum vector'. This weighted sum vector for each requirement is divided by the average weight of respective requirement and gives a value is called 'eigenvector (λ)'. The largest value of eigenvector is known as 'λ_{max}'. This pair-wise comparison technique is continued until the eigenvector reaches the maximum value, i.e., λ_{max}.

Consistency measurement

After the matrices are developed and all pair-wise comparisons are obtained, eigenvectors and the maximum eigenvalue (λ_{max}) for each matrix are then calculated. The λ_{max} value is an important validating parameter in pair-wise comparisons. The Consistency Ratio (CR) (Saaty, 2000) is an important parameter for checking consistency of the estimated vectors. The consistency ratio is calculated as per the following steps:

a) The eigenvector and λ_{max} for each matrix of order n are calculated.

b) The consistency index (CI) for each matrix of order n is computed as follows: $CI = (\lambda_{max} - n)/(n-1)$.

c) The consistency ratio is calculated by:

$$CR = CI / RI$$

RI is a known as "Random Consistency Index".

Table 3 shows the value of RI for matrices of order 1 to 9 obtained by approximating RI using a sample size of 500 (Saaty, 2000). According to Saaty, the Consistency Ratio, less than or equal to the limit of 0.10, reveals a reasonable level of consistency and when this value is higher than 0.10, revisions of the judgement are recommended.

Table 3: Average random index (RI) based on matrix size

n	RI	n	RI
1	0.00	6	1.24
2	0.00	7	1.32
3	0.58	8	1.41
4	0.90	9	1.45
5	1.12	10	1.49

Step 4: List of Technical requirements ('voice of engineer')

The QFD method must come up with the technical requirements that will affect one or more of the customer requirements. These technical requirements directly affect the customer requirements and are expressed in measurable terms. The customer requirements are very difficult to implement until they are translated into specific engineering requirements.

Step 5: Develop a relationship matrix between the customer requirements and technical requirements

The customer requirements are organized in product planning matrices. Management control requirements, national and international standards and regulatory requirements are also critical factors and need to be addressed. To respond to the customer requirements, establishment of technical requirements and organization of these requirements into logical categories are necessary. Technical requirements should be meaningful, measurable, practical and global.

The next step is to develop the relationship between customer requirements and technical requirements by using 5-3-1 weighting factor to indicate the strength of the relationship (strong, medium, and weak). The Figures 49, 50, 51, and 52 are taken from, 'Quality function deployment, by A.J.Lower and K. Ridgway (2001)'.

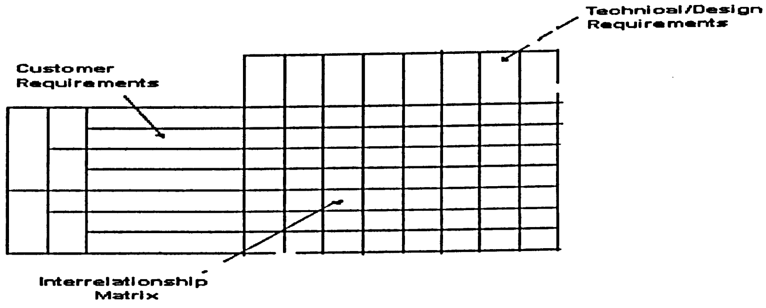


Fig 49: The Interrelationship matrix

Step 6: Customer rating of the competition

The next step is competitive evaluation of products. The step includes the rating of the products on a scale of 1 to 5 with '5' indicating that the product fully satisfies the customer requirements. The customer perceptions, observed in the market survey, including relative importance of customer requirements, company and competitor performance, are used in meeting these requirements. The competitive assessments are divided into two categories, customer competitive assessment and technical competitive assessment.

Customer competitive assessment: The customer competitive assessment makes up a column on the right side of the interrelationship matrix for each customer requirements. Numbers 1 to 5 are used for competitive evaluations. Number 1 means the worst competitor and number 5 means the best competitor. These ranking can plot each customer requirements using different symbols for each product. The customer competitive assessment is a good process to determine the customer requirements and to identify the areas to concentrate on the next design.

Technical competitive assessment: The technical competitive assessment makes up a row beneath the relationship matrix for each technical requirement. After units are established, the products are evaluated for each technical requirement. Number 1 to 5 is used for competitive evaluations, 1 means the worst and 5 means the best. These rankings are plotted for each technical requirement using the same symbols used in the customer competitive assessment.

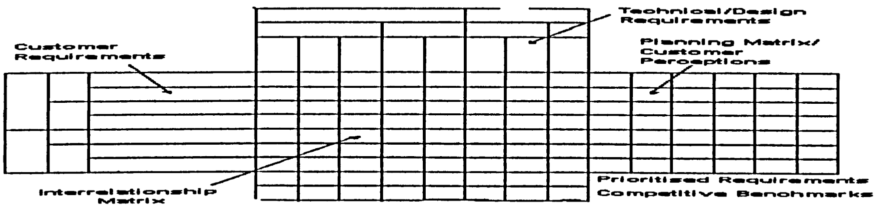


Fig 50: The Interrelationship matrix with competitive assessment

Step 7: Target values for technical requirements

At this point preliminary target values for technical requirements have to be developed considering data gathered during the technical evaluation.

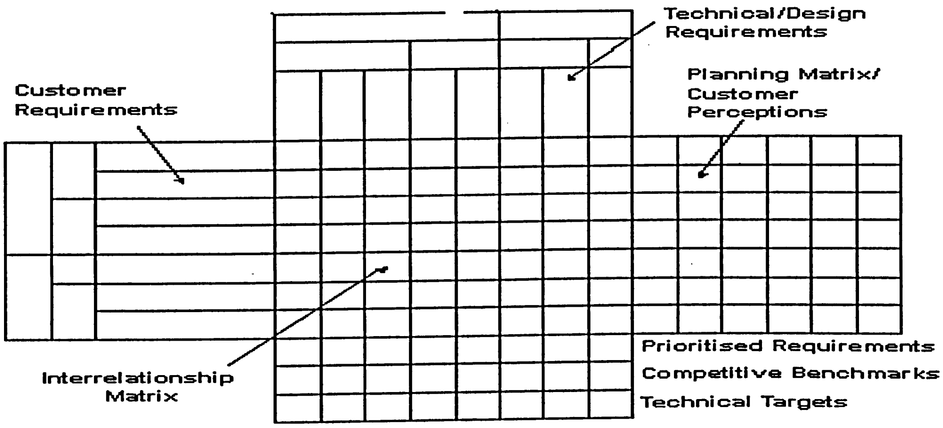


Fig 51: The Interrelationship matrix with target values

Step 8: Develop an interrelationship matrix between pairs of technical requirements

The correlation matrix defines the roof of the House of Quality. It is used to identify the interrelationships between pairs of technical requirements. Different symbols are used to mention the strength of the interrelationships.

+2 = represents a strong positive relationship = SP.

+1 = represents a positive relationship = P.

-1 = represents a negative relationship = N.

-2 = represents a strong negative relationship = SN.

0 = no relationship (empty)

The user can identify the important technical requirements by the correlation matrix. The correlation matrix allows the user to represent points at which trade-offs must be made. If trade-offs are not identified and resolved, then it will often lead to unfulfilled needs, engineering changes, poorer quality and increased costs. Few of the trade-offs may require top-level managerial decision, because they involve cross-functional area boundaries. However, though it is difficult, an early resolution of trade-offs is vital to shorten product development period.

Another method is to simplify the interrelationships by using only two kinds of relationships, mainly: positive and negative relationship. The symbol '+' is used for synergy and the symbol '-' is used for compromise.

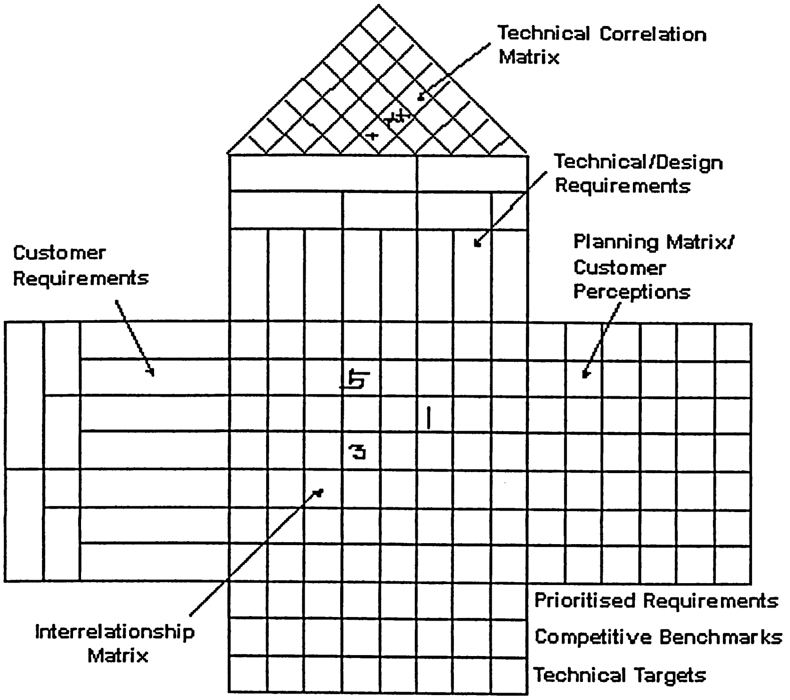


Fig 52: A House of Quality (Lowe, A.J. et al., 2001)

3.3 Concept development by Pugh decision matrix method

3.3.1 Introduction

In this stage, alternative product concepts are developed considering current approach and technology as well as alternative approaches and technologies. Extensive review of literature and brainstorming are useful for this purpose. Development of alternative concepts also includes product benchmarking and developing derivative ideas. Alternative concepts are evaluated by using concept selection matrix. This matrix lists customer requirements down the left side of the matrix.

i) Pugh decision matrix method for selection of concept:

This is a scoring matrix solution for concept selection. It helps to determine which solutions are 'better' or more important than others are. This method can be used before taking decision on the final design of the product after QFD product planning method. In this method, options (solutions) are assigned scores relative to function using a symbolic approach. One symbol is used for the better, another for neutral, and another for worse than the baseline. These are converted into scores and the selection process is used on the basis of the consolidated scores. One should have many solutions so that one can select the best out of them. This tool is also called 'Criteria based matrix'. The Pugh decision matrix method is a team-based procedure for concept generation and selection. Several concepts are evaluated based on their strengths and weaknesses against a reference concept called 'base concept'. The base concept is the best current concept at each function of the matrix.

There are three main steps in this method (Pugh decision matrix method):

a) Comparison of the different alternative concepts,

b) Scoring concepts relative to one another (creating the strong alternative concepts from weaker concepts) and iteration evaluation method , and

c) Arriving at an optimum concept that may be a variant of the best of other concepts.

The Pugh decision matrix method compares several different concepts against a base (datum) concept, and then creates stronger concepts and eliminates weaker ones until an optimal concept is achieved. If the problem is to redesign an existing product then the existing product can be used as the base (datum). For each comparison, the product must be evaluated as being better (+1), the same (0), or worse (-1). Finally, Pugh decision matrix method obtains the final solution. The Pugh decision matrix method is also useful method because it does not need a great amount of quantitative data on the design concepts, which generally is unavailable at this point in the process.

Chapter 4

Design and concept development of connector for self-reconfigurable modular serpentine sensing robot

4.1 Introduction

The main objective of this chapter is to design a connector for a self-reconfigurable modular serpentine sensing robot by using the QFD and the Pugh decision matrix methods. The first part of this chapter is concentrated on the QFD method and developed a base of design concept. The last part is focused on the Pugh decision matrix method to finalize the design concept of the connector.

4.2 Development of a design base for designing of connector for self-reconfigurable modular serpentine sensing robot by QFD method

Step1: Customer needs and requirements

The customers of this project are hypothetical teams. This concept can be used in robotics industries that are manufacturing self-reconfigurable modular serpentine sensing robots. The customer needs / specifications are listed below:

- Loading capacity of the self-reconfigurable serpentine sensing robot: the robot can carry the maximum amount of load that is feasible.

- Mechanical forces transfer: It includes types and quantity of mechanical forces transmitted from one module to another (axial, bending, torsion etc.).
- Data transfer: It includes quality, quantity, reliability and speed of data transmitted from one module to another.
- Power transfer: It includes quantity and reliability of power transmitted from one module to another module.
- Physical robustness- safety and security: Strength and reliability of the connector
- Cost: It includes maximum permissible manufacturing cost, cost of tooling, investment and depreciation.
- Maintenance: It includes number of parts and moving parts inside the connector (or, Servicing interval, inspection, exchange and repair, painting and cleaning etc)

Step 2: Specific customer requirements

These general requirements have been broken down into requirements that are more specific in terms of engineering point of view and cost is not considered. For this purpose, first the requirements are consolidated and then prioritize them by using pair-wise comparison method.

- Transfer of Mechanical forces- Connector needs to transmit different types of forces like axial forces, shear forces and torque.
- Transfer of Data- Quality, quantity, reliability and speed of data transmitted from one to another module.

- Transfer of Power- Quantity and reliable electrical power transmitted from one module to another.
- Connection mechanism- It includes the types of locking and unlocking mechanism, automatic/ mechanical, simple & secure etc to connect one module with other module.
- Degree of freedom- Number of positions available to connect with other modules

Step 3: Weighted priority of customer requirements

Pair-wise comparison method

The preference input for the pair-wise comparison matrix is determined after estimating to what degree one factor is preferred to another (refer to Table 4 and Table 5). The judgments are entered using the fundamental scale (Table 2).

Table 4: Scale of relative importance – level 1

Base requirements (Criteria)	Subjective rating	Compared criterion	Value
Connection Mech.	Essentially more important than	DOF	5
Connection Mech.	Essentially more important - midvalue	Tranf.of M. For.	4
Connection Mech.	Essentially more important - midvalue	Tranf. of Data	4
Connection Mech.	Weak importance – midvalue	Tranf. of Power	2
Transfer of Power	Essentially more important than	DOF	5
Transfer of Power	Essentially more important - midvalue	Tranf. of M. For.	4
Transfer of Power	Weak importance of one over another	Tranf. of Data	3
Transfer of Data	Essentially more important - midvalue	DOF	4
Transfer of Data	Weak importance of one over another	Tranf. of M.For.	3
Tranf. of M. Force	Weak importance of one over another	DOF	3

Table 5: Base criteria matrix

Requirements (Criteria)	Degrees of Freedom	Transfer of Mechanical Forces	Transfer of Data	Transfer of Power	Connection Mechanism
Degrees of Freedom	1	1/3	¼	1/5	1/5
Transfer of Mechanical Forces	3	1	1/3	¼	¼
Transfer of Data	4	3	1	1/3	¼
Transfer of Power	5	4	3	1	½
Connection Mechanism	5	4	4	2	1
Total	18.00	12+1/3	8+1/4+1/3	3+1/5+1/4+ 1/3	2+1/5

Weight calculations of the base requirements

The row of average weight of the pair-wise comparison matrix is calculated (after converting it to decimals) as shown in Table 6 and Table 7:

Table 6: Weight calculation-1

Requirements (criteria)	Degrees of Freedom	Transfer of Mechanical Forces	Transfer of Data/Power	Connection Mechanism	Connector Strength
Degrees of Freedom	1	1/3= 0.33	1/4= 0.25	1/5= 0.20	1/5= 0.20
Transfer of Mechanical Forces	3	1	1/3= 0.33	1/4= 0.25	¼= 0.25
Transfer of Data	4	3	1	1/3= 0.33	1/4= 0.25
Transfer of Power	5	4	3	1	½=0.50
Connection Mechanism	5	4	4	2	1
Total	18.00	12.33	8.58	3.78	2.20

The numbers in the matrix of each cell is divided by their respective column total to produce the normalized matrix along with the average of various rows as each requirement in Table 7.

Table 7: Weight calculation-2 (Normalized matrix)

Requirements (criteria)	**Degrees of Freedom**	**Transfer of Mechanical Forces**	**Transfer of Data**	**Transfer of Power**	**Connection Mechanism**	**Average Weight**
Degrees of Freedom	1/18 =0.05	0.33/12.33 =0.03	0.25/8.58 =0.03	0.20/3.78 =0.05	0.20/2.20 =0.09	0.05
Transfer of Mechanical Forces	3/18 =0.17	1/12.33 =0.09	0.33/8.58 =0.04	0.25/3.78 =0.07	0.25/2.20 =0.11	0.10
Transfer of Data	4/18 =0.22	3/12.33 =0.24	1/8.58 =0.12	0.33/3.78 =0.09	0.25/2.20 =0.11	0.15
Transfer of Power	5/18 =0.28	4/12.33 =0.32	3/8.58 =0.35	1/3.78 =0.26	0.50/2.20 =0.23	0.29
Connection Mechanism	5/18 =0.28	4/12.33 =0.32	4/8.58 =0.46	2/3.78 =0.53	1/2.20 =0.46	0.41
Total	1.00	1.00	1.00	1.00	1.00.	1.00

Consistency Ratio

At first, the average weight of each requirement in Table 7 (normalized matrix) is multiplied by the comparison matrix as in Table 5 (base criteria matrix) and it produces a new vector as shown in the Table 8. This weighted sum vector for each requirement (criterion) is divided by the average weight of that respective requirement and the average of these values gives the maximum eigenvector (λ_{max}) (refer to Table 9).

Table 8: Calculation of Weighted sum vector

Requirements (criteria)	Degrees of Freedom	Transfer of Mechanical Forces	Transfer of Data	Transfer of Power	Connection Mechanism	Weighted sum vector
Degrees of Freedom	1*0.05	0.33*0.10	0.25* 0.15	0.20* 0.29	0.20*0.41	0.26
Transfer of Mechanical Forces	3*0.05	1*0.10	0.33* 0.15	0.25* 0.29	0.25*0.41	0.48
Transfer Of Data	4*0.05	3*0.10	1*0.15	0.33* 0.29	0.25*0.41	0.85
Transfer of Power	5*0.05	4*0.10	3*0.15	1*0.29	0.50*0.41	1.60
Connection Mechanism	5*0.05	4*0.10	4*0.15	2*0.29	1*0.41	2.24

Table 9: Calculation of consistency vector

Requirements (criteria)	Average Weight	Weighted sum vector	Consistency vector	
Degrees of Freedom	0.05	0.26	0.26/0.05	5.20
Transfer of Mechanical Forces	0.10	0.48	0.48/0.10	4.80
Transfer of Data	0.15	0.85	0.85/0.15	5.67
Transfer of Power	0.29	1.60	1.60/0.29	5.52
Connection Mechanism	0.41	2.24	2.24/0.41	5.46

$\lambda_{max} = (5.2+4.8+5.67+5.52+5.46)/5 = 5.33$

Calculation of Consistency Ratio:

CR = Consistency Index/ Random Index = CI/ RI

The consistency index is computed as CI = (λ_{max} -n)/ (n-1). Substituting the values CI becomes, CI = (5.33 – 5) / (5-1) = 0.0825.

The consistency ratio is equal to the consistency index divided by the random index (RI). For n = 5, RI is 1.12 (Table 2). So the consistency ratio for this case is CR = 0.0825/1.12 = 0.07. The consistency ratio is less than the limit of 0.10. Therefore, the subjective pair-wise comparisons of the criterion are reasonably consistent.

Result of the customer priority analysis:

Requirements	Weighted Factor(%)
DOF(1)	05
Mech(2)	10
Data (3)	15
Power (4)	29
Connection Mechanism(5)	41

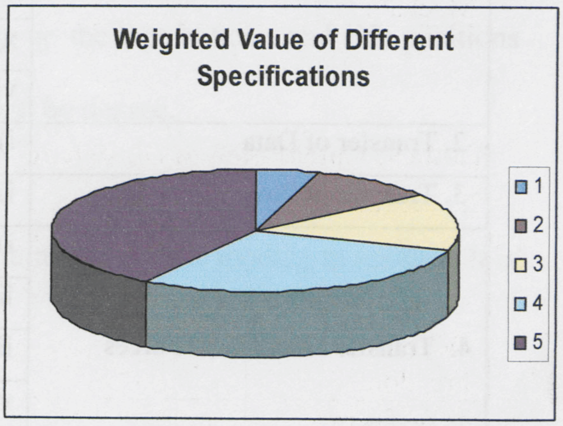


Fig 53: Weighted value of different requirements

From the customer priority analysis (refer to Fig 53), it is clear that for designing the product we should thrust on the connection mechanism and transfer of power. The next important factors are data and mechanical force transmission. Degree of freedom is a least important factor because the connector is attached with the module and that module is assumed to provide the degree of freedom for the robot.

Step 4: List of Technical requirements

Table 10 shows the transformation of customer requirements into technical requirements.

Table 10: Transformation of customer requirements into technical requirements

Customer requirements	Technical requirements (in units)
1. Connection Mechanism	i) Secured connection-maximum force (N)
	ii) Automatic/ Mechanical (%) connection
	iii) Power required to connect & disconnect (W)
	iv) Time to connection (s)
	v) Position precision (mm)
	vi) Range of alignment (degree)
2. Transfer of Data	i) Signal (bps)
3. Transfer of Power	i) Total Power (W)
4. Transfer Mechanical Forces	i) Axial Forces (N)
	ii) Torque (Nm)
	iii) Bending (N)
	v) Twisting (N)
5. Degree of Freedom	i) Number of positions available (number)

Secured connection-maximum force (N)

It is the strength of the connector. It means the maximum force that the connector can withstand before failure of the connecting system.

Automatic/ Mechanical connection (%)

The connection system should be mechanical as much as possible. The system includes a) guide to connect the modules, b) connection of the modules, c) security of the connection, and d) disconnection. For measuring these requirements, percentage of mechanical solution is the parameter.

Power required to connect and disconnect (W)

The total power that is required for connection and disconnection of the whole system.

Time to connect and disconnect (s)

The total time that is required to connect and disconnect the whole system.

Position precision (mm)

It is a very important requirement. For a better connecting system, the connection mistake should be minimum.

Range of alignment (± degree)

The range of alignment refers to lining up the top, bottom, and side positions to connect with other modules. This is measured by degree.

Signal (bps)

Total quantities of those data are transmitted from one module to another. It is measured in terms of bps.

Total Power (W)

Total power is required for connecting, disconnecting and all other robotic actions. It can be transmitted from one module to another.

Axial Forces (N)

Total amount of force can be transmitted from one module to another.

Torque (Nm)

The connector (Nm) can carry torque.

Bending (N)

Amount of bending load that can absorbed by this connector (N).

Twisting (N)

Amount of twisting that load can be carried by this connector (N)

Number of positions available (number)

The numbers of positions are available to connect with the other modules (number).

Step 5: Development a relationship matrix between the customer requirements and technical requirements

Table 11 shows the relationship matrix between the customer requirements and technical requirements.

Table 11: Relationship matrix between the customer requirements and technical requirements

Technica Requ. / Customer Requits	PRIORITY	SECURED CONNECTION MAX. EFFORT	AUTO/MECHANICAL	POWER REQUIRED	TIME OF CONNECTION	POSITION PRECISION	RANGE OF ALIGNMENT	SIGNAL TRANSFER	TOTAL POWER TRANSFER	AXIAL FORCE TRANSFER	TORQUE	BENDING FORCE TRANSFER	TWISTING FORCE TRANSFER	NO. OF POSITIONS AVAILABLE
Connection Mechanism	0.41	5	5	5	5	5	5		1	3	3			
Transfer of Data	0.15							5	1					
Transfer of Power	0.29							1	5					
Transfer of Mechanical Forces	0.10	5	1							5	5	5	5	
Degree of Freedom	0.05						1							5

◙= Strong relationship= 5
●= Moderate relationship= 3
▲= Weak relationship= 1
Empty= No relationship= 0

Step 6: Competitive products analysis

Based on the customer requirements and technical requirements, customer requirements assessment and technical requirements assessment evaluation have developed of competitive products. This study considers Dragon connector of Martin Nilsson, 2002 and MTRAN connector of Murata et al., 2000 because these connectors are the current development in this field of research and very near to the concept of the required design.

i) Dragon Connector

The Dragon (Distributed Real-time Autonomously Guided OrgaNism) connector is a strong, lightweight and genderless connector which is able to align large offsets laterally (± 15 mm), directionally and rotationally (± 45^0) (Nilsson, 2002a, and 2002b). This connector has a polymeric 2-cone-2-funnel structure (refer to Fig 54). There are three basic components of a Dragon connector: the guide, the shell and the latching spring. While the shell, a thin layer of the connector's diameter takes most of the load, the guide, shaped as two funnels and two mating cones, helps to align the connector. The diameters of guide and shell are 64 mm and 75 mm respectively. The two connectors are connected through the latching spring. This latching mechanism has 0.2 mm thin steel spring blade that goes into 1.5 mm deep cavity of the shell. The blade has a load bearing element and a spring. At the time of locking, the blade expands and pushes against the shell. For unlocking, a SMA wire running along the inside surface of the spring, pulls the spring together. Manual unlocking is possible by inserting pins or screws in four threaded holes in each connector, which compresses the spring and unlocks the connectors. The latching mechanism is strong in the axial direction with a buckling load of 37 KN and maximum axial load for shear of 11 KN. The connector weighs 175 gms but can take a load of 70 kgs. The outer diameter of the connector is 75 mm. The sensing device is placed centrally inside the guide cone. For transferring energy and signals, this connector contains twelve 4 mm spring-loaded copper contact elements for withstanding high currents. The prototype guide is made of polyoxymethylene (POM). This material has low friction. The shell is made of both aluminum (pb-106 medium-strength alloy) and steel.

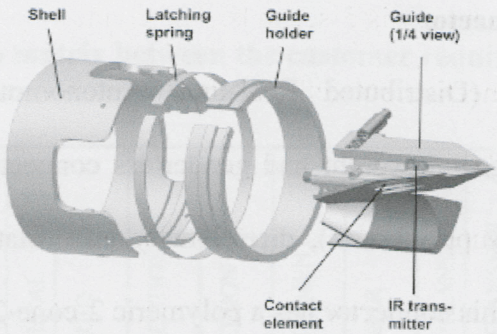


Fig 54: A Dragon connector (Nilsson, 2002a)

ii) MTRAN Connector

The MTRAN connector is simple and reliable (Murata et al. 2000, 2004). An internally balanced magnetic unit (IBMU) is adopted in this connection mechanism. The passive part has all the control circuits. The passive part consists of two part pair electrodes (anode and cathode), four samarium-cobalt permanent magnets (S poles on the surface), and one electrode for a serial communication. The connecting force i.e., 83 N is achieved through the magnets.

The active part is another part of the connecting mechanism. Non-linear springs, SMA (shape memory alloy) coils and four permanent magnets (N poles on the surface) are fixed on the connecting plate.

The force of the permanent magnet is sufficient to align and hold the modules. It requires the same force to detach the modules. The non-linear springs are designed in such a way that they have a slightly lower force than magnets when they are compressed. For this reason, a small amount of additional force is required for detachment. At the time of detachment of the SMA, the coil spring is heated by an electrical current and is extended to memorize length and then pushes down the magnets (refer to Fig 55). The power consumption required for unlocking is 180 J and the elapsed time detachment is 5 seconds. The connecting force between modules is about 83 N. The connection strength (to attach) and reduced connection strength (to detach) are 3.6 kg and 0.3 kg respectively.

For power supply and serial communication from module-to-module, connecting faces also have electrodes. Connection surfaces are made of glass-epoxy fiber circuit to reduce electrical wiring and total weight. There are on-board host PC and relay PIC microprocessor in each module that control servomotors and SMA actuators. Communication between host PC and relay PIC and between relay PIC and modules are achieved by 4800 bps serial communications. Each module weighs around 400 gms.

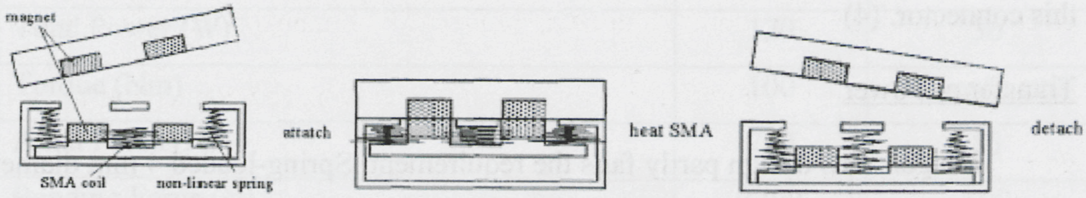


Fig 55: The connection mechanism of MTRN connector (Murata et al. 2000)

Competitive assessment: By evaluating the customer requirements and the technical requirements, the product is rated on 1 to 5 scales based on customer satisfaction.

1 = Worst condition (strong negative value), the design fully fails the requirements,

2 = Moderate negative condition, the design partly fails the requirements,

3 = Equal condition, the design equally meets the requirements,

4 = Moderate positive condition, the design partly exceeds the requirements,

5 = Best condition, the design fully exceeds the requirements

Customer requirements competitive assessment

Connection mechanism

Dragon: this connector partly exceeds the requirement, because it is strong and easy mechanism. (4)

MTRAN: this connector partly fails the requirement, due to magnetic forces are acting for connection mechanism, and no extra mechanical device is used for locking purpose. (2)

Transfer of Data

Dragon: this design meets the requirement. Optical channels are using in this connector. (3)

MTRAN: this design partly exceeds the requirement. CAN system is used in this connector. (4)

Transfer of Power

Dragon: this design partly fails the requirement. Spring-loaded 4 mm diameter copper rods are used. (2)

MTRAN: this design partly exceeds the requirement. Ordinary electrodes with gold deposit are used. (4)

Transfer of Mechanical forces

Dragon: this design partly exceeds the requirement. Mechanical forces are transmitted very good due to strong connection and locking mechanism. (4)

MTRAN: this design partly fails the requirement. Mechanical forces are not transmitted very large amount due to there are no mechanical locking system. (2)

Degree of freedom

Dragon: the design meets the requirement- (3)

MTRAN: the design partly fails the requirement- (2)

Table 12 shows the list of the technical requirements of the Dragon and the MTRAN connectors

Table 12: Technical requirements of Dragon and MTRAN connector

Technical requirements	Dragon	MTRAN
Secured connection-maximum force (N)	700	83
Automatic/ Mechanical connection (%)	50	100
Power required to connect and disconnect (W)	0.3	10
Time to connect and disconnect (s)	10	17.5
Position precision (mm)	2	1
Range of alignment (± degree)	45^0	60^0
Signal (bps)	2400	4800
Total Power (W)	120	36
Torque (Nm)	100	1.9 each axis
Axial Force (N)	700	83
Bending Force (N)	3700	400
Twisting Force (N)	1400	200
Number of positions available	5	4

Step7: Target value for technical requirements

At this point, preliminary target values for technical requirements have to be established to obtain the new connector design (Table 1). This study has considered GMD snake 2 type serpentine modular robot and sensing application to limit the study. For making this GMD snake 2 type self-reconfigurable modular serpentine sensing robot, a maximum of 15 modules and the latest Generation-3 (Yim, M., 1993) type module are used. The size of this cube-shape G3 module is 50x50x45 mm and weight is 200gm (mass). The speed of GMD snake 2 serpentine robot is 0.1 m/sec.

In the serpentine robotic systems, bending, shearing and twisting forces are calculated based on the following dimensions (Shammes et al., 2003): n= total number of modules used for making our serpentine robot, L= size of each module (Yim-G3-polybot), i.e., 5x5x4.5 cm and W = weight of the each module, i.e., (200 * g) gm-force (Yim, M., 1993).

$T_{bending}$ (Bending torque $= n^2 \frac{WL}{2}$, $T_{twisting}$ (Twisting torque)= $(n-1)^2 \frac{WL}{2}$.

Bending, shearing, and twisting forces are calculated on basic of the above equations in worst-case scenarios. All calculations are available in the 'force and stress analysis' portion of this project, ref. 4.5. Minimum forces are bending force 551.81 N, shearing force 480.20 N, and twisting force 480.20 N. In this project, the forces are bending 600 N, shearing and twisting forces 500 N. The total power consumption of this robot is 40 Watts and torque 12 Nm.

After considering all factors, the study has standardized the design of the required serpentine sensing robot with following specifications:

1) Length = 90 cm.

2) Speed of robot = 0.1 m/sec.

3) Total number modules = 15.

4) Size of module (G3-Polybot) = 5x5x4.5 cm.

5) Weight of module (G3-Polybot) = 200 gm (mass).

6) Bending = 600 N.

7) Twisting = 500 N.

8) Torque = 12 Nm.

9) Power = 40 Watts (total).

Secured connection-maximum force (N)

It is established that in general a maximum amount of connection forces of 300 N is required for securing the connection after researching all types of serpentine sensing robots.

The target value is 300 N.

Automatic/ Mechanical connection (%)

The design connector must be secured and preserved in case of missed electricity. The target value is 75%.

Power required to connect and disconnect (W)

The target value is 5 Watts

Time to connect and disconnect (s)

The time to connect and disconnect the modules depends on the application.

The target value is 5 sec.

Position precision (mm)

In this application position, precision must be as high as possible.

The target value is 1 mm.

Range of alignment (± degree)

The range of alignment refers to lining up the top, bottom, side positions to connect with the other modules. This is measured by the degree. The target value is $\pm 60^0$.

Signal (bps)

The target value 9600 bps

Total Power (W)

The target value is 40 Watt

Axial force (N)

The target value is 300 N

Torque (Nm)

The target value is 12 Nm

Bending force(N)

The target value is 600 N

Twisting force (N)

The target value is 500 N

Number of positions available (number)

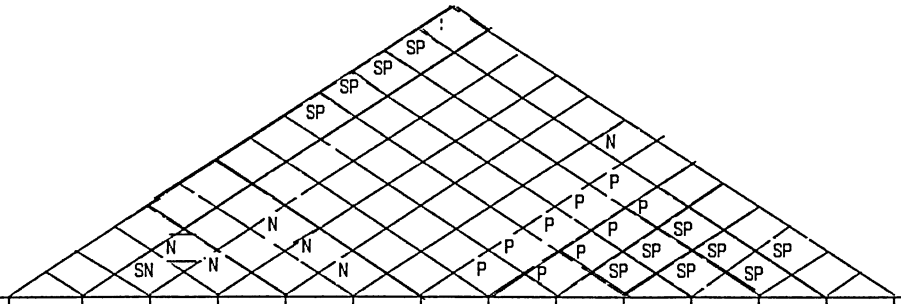
The target value is 5

Step 8: Development of an interrelationship Matrix between pairs of technical requirements

These interrelationships of technical requirements are combined and form a matrix.

House of Quality

The combined matrix is developed after combining all steps of the matrix from 1 to 8. This combined matrix is called 'House of Quality (HOQ)' shown in Fig 56. In this HOQ, the main two requirements are considered and developed relationship between them, i.e., customer requirements and technical requirements. For an example, connection mechanism (customer requirements) and secured connection (technical requirements) have a good relationship, i.e., 5. In the roof of the combined matrix, there are interrelationships between technical requirements. For an example, auto/mech to connect with power to connect and disconnect are strong negative relationship (SN). The last right side column of this HOQ, is the customer competitive assessments for each customer requirement, 5 means good competitor and 1 means worst competitor. The bottom part (row) of this HOQ, is the technical competitive assessments for each technical requirement, 5 means good competitor and 1 means worst competitor. The last row indicates the target values of this project for designing of the connector for the self-reconfigurable modular serpentine sensing robot.



Tech. requi. / Customer requi	Priority / Weight	connection maximum forces	Auto/Mech to connect	Power to connect and disconnect	Time to connect	Position precision	Range of aligement	Transfer of signal	Transfer of power	Transfer of axial force	Torque	Bending force	Twisting forces	Number of position	Competitive Evaluation 1 2 3 4 5
Connection mechanism	0.41	5	5	5	5	5	5		1	3	3				1 M 3 D 5
Transfer of Data	0.15							5	1						1 2 D M 5
Transfer of Power	0.29							1	5						1 D 3 M 5
Transfer of Mechanical forces	0.1	5	1							5	5	5	5		1 M 3 D 5
Degree of freedom	0.05						1							5	1 M D 4 5
Technical Evaluation Best 5															
4		D		D	D	M	M	M	D	D	D	D	D		
3			D				D							D	
2		M	M	M	M	D		D	M	M	M	M	M	M	
Worst 1															
Target value		300	75	5	5	1	60	9600	40	300	12	600	500	5	

Fig 56: The House of Quality

5 = Strong relationship,
3 = Moderate relationship,
1 = Weak relationship,
Empty = No relationship

SP = Strong positive relationship,
P = Positive relationship,
SN = Strong negative relationship,
N = Negative relationship
Empty = No relationship

D = Dragon connector

M = MTRAN connector

4.3 Concept development of design of connector for self-reconfigurable modular serpentine sensing robot

In this section, there are four steps: 1) development of the functions, 2) development of the concepts of different functions, 3) creation of concept combination matrix, and finally, 4) use of Pugh decision matrix method for selection of the best concept for the connector design.

Step 1 & 2:

In this section, four functions have been considered, i.e., connection of modules, automatic/mechanical connection, power transfer, and data transfer. Each function consists of different concepts.

Function 1: Connect modules

This function is a very important factor to connect and disconnect one module with and from another module. It should be simple and reliable. The two main mechanisms of the connect modules are a) the locking mechanism, and b) the unlocking mechanism. The locking mechanism is one of the most important parts of this function. Power consumption should be minimum at the time of locking and unlocking. The connection system should carry large axial, bending and twisting forces.

There are many existing connect modules concepts available in the market. Some concepts are still in research stage. This study considers a few of them.

First concept: Male (plug) and female (receptacle) lamella mechanism

In this concept, the connector has mainly two parts, the male (plug) part and the female (receptacle) part (refer to Fig 57). When these two parts are connected, this joint is highly secured to the transfer maximum amount of mechanical forces. During the connecting process, the lamellae of male part comes in contact with the female lamellae, and the faces of the heads slide against each other to a point where the shoulders move into each other and engage. The male and female parts are engaged in such a way that the male lamellae engage the female lamellae by the shoulders. This connector can transmit axial force through lamellae and sheer force through male (plug) and female (receptacle) housing.

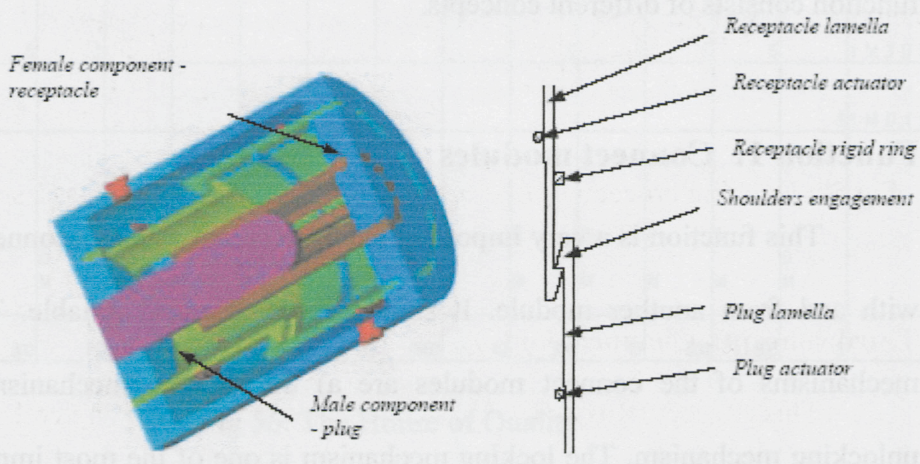


Fig 57: The section of connection configuration (left). The lamellae in an engaged position (right) (Badescu and Mavroidis, 2001)

Second concept: S- Type engagement latch

In this concept, the connector has three parts: an active part, a passive part and a module body. The connection is made in between active and passive parts shown in

Fig 58. Both parts are square shaped. The face of the active part is of the same dimension as those of the faces of the passive parts. The face of active part has two sockets to receive the pins of the passive face. As the pins of passive face slide inside the socket of active face, their dome-shaped heads force an engagement latch to rotate in a direction perpendicular to the path of the passive pins. Ultimately, the passive pins are modular and fully inserted, exposing a lateral groove into which the engagement latch edge is forced by a spring action. This latching or engagement process is completely mechanical. For disconnecting, discussed Chapter 2.3 (vi).

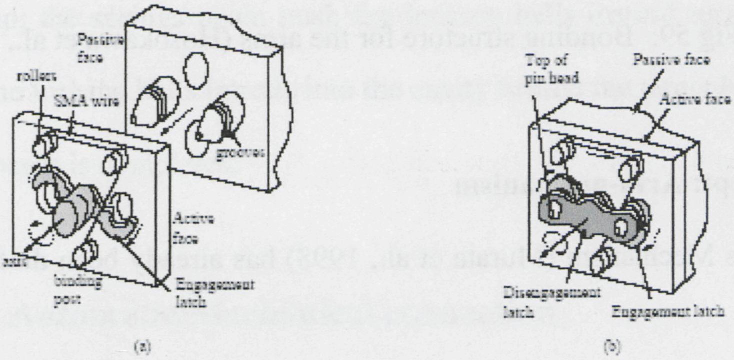


Fig 58: Docking procedure- (a) engagement, (b) disengagement (Castano, A.,2000)

Third concept: Channel and Key

This concept (Rus and Vona 1999) was discussed in Chapter 2.

Fourth concept: Blade and Cavity

This concept (Nilsson, 2002a, and 2002b) was discussed in detail in Chapter 2.

Fifth concept: Lock and Key

It is a very simple 'lock-key' structure (Hosokawa et al., 1998). One important point for this concept is lack of "polarity (male/female discrimination- refer to Fig 59)". This system consists of an arm that is equipped with both a lock part and a key part. The two arms are connected together by inserting the pin into the notch. This connection is stable for bending moment and compressive forces.

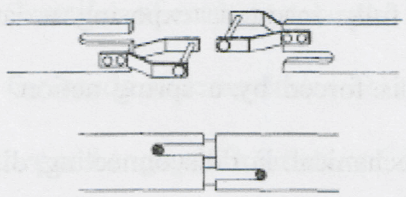


Fig 59: Bonding structure for the arms (Hosokawa et al., 1998)

Sixth concept: Arm-mechanism

This Mechanism (Murata et al., 1998) has already been discussed in Chapter 2.

Seventh concept: Magnetic connection

This concept (Murata et al., 2000) has been discussed in detail in Chapter 1 in the competitive products analysis portion.

Eighth concept: Ball-Socket joint

This concept of locking and unlocking systems is a form of a ball-and-socket joint (RTI international, 2004). This concept is already existed in the market. However, the first time this system is used in self-reconfigurable modular sensing robotic systems. The concept can tolerate significant amount of initial misalignment because it has an alignment cone that can guide the ball into the socket. There are main two parts: a target ball assembly, the socket assembly. The socket consists of an alignment cone, which is tapered down to a central cylindrical bore ending in a cup. The bore and the cup are of same dimension to receive the target ball. The socket assembly has three locking balls, smaller than the target ball. The locking balls are spring-loaded against hard stops on a ring and the geometry of the ring and holes is such as to allow the balls to intrude part way into the central cylindrical bore. When the target ball is inserted into the socket and is pushed towards the cup, it pushes the locking balls out of the way against their spring loads. As the target ball comes to a stop in the cup, the springs again push the locking balls inward against their hard stops so that the locking balls intrude into the cavity behind the target ball. Hence, the connection process is completed.

Function 2: Automatic/Mechanical connection

First concept: Manual force

In this concept, an outside force connects the connecting parts manually. This system is fully mechanical.

Second concept: Magnetic system

In this concept, the connecting parts are connected by a magnetic force. Different types of magnet combinations are used in this function.

Different types of magnetic combinations for connecting two modules are:

a) One connecting part is ferromagnetism; another part is ferro alloy,

b) Both connecting parts are magnets and they have opposite polarities (one south and another north).

Third concept: Sensing system

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The third concept is to connect the connecting parts through sensing magnetic process. Connectors need sensors for sensing the relative position of a mating connector. The shape of the connector must allow convenient sensor placement, including screening and sensor protection.

Fourth concept: Rack-pinion mechanism

The fourth concept, the connecting parts are connected by a rack-pinion mechanism. The contraction and expansion of the connecting parts are possible through this system.

Function 3: Power Transfer

The connector is also responsible for transmitting power between two connected modules. This is an important function and it can be difficult to implement. A small number of existing systems, allowing power transmission through connectors, demonstrates this function. The electrical contact parts should be designed in such a way that it can minimize oxidization of contact surfaces.

First concept: Spring loaded copper rods

In this concept, the connector consists of 12 numbers 4 mm diameter spring-loaded copper rods elements, able to carry high currents. The element's tips are flat, at an oblique angle of approximately 15^0. At the time of connection, the elements slide over the large surface area, providing a self-cleaning electrical contact.

Second concept: Plug contact

The second concept is a plug type mechanical connection. There are different types of systems in this concept as follows:

a) existing plugs available in the market, and

b) design for specific requirement.

Third concept: Coil system

In this system, power can be transferred from one module to another module through coils. When current passes through the coils, it creates the magnetic field. This magnetic field again creates the current in another coil that is close to the first one.

Fourth concept: Electrodes with gold deposit

This is a very recent development for transmitting a large current between two modules. Ordinary electrodes with gold deposit can be used. It can carry several amps per connection.

Fifth concept: Electromagnetic clutches

The power can be transferred from one module to another module by electromagnetic clutches.

Sixth concept: Male and Female conductive materials

The connector has male and female parts. The male part can be made of conductive material (outside portion). The female part's housing (inside face) can be made of conductive material so that they (male-female part) can carry current at the time of connection.

Function 4: Data Transfer

There are two sub-functions of this function. The main function is to transfer data from one module to another module. One sub-function is receiving data from a module and another sub-function is sending data to the other module. However, the same types of concepts are used in these two sub-functions. This study considers these two sub-functions as a one main function. Data can transmit through contact and non-contact of two mating parts. The contact method means the data can transmit when two parts are contact each other, and the non-contact method means that the data can transmit without contact of two parts.

First concept: IR sensor

In this concept, IR (Infrared) receivers and transmitters of the module are used for transmission of data from one module to another module. This connection establishes serial communication with other modules.

Second concept: Optical channels

The second concept is optical channel. In this system, information can be transmitted in the form of light impulses. Data can also be encoded by light impulses. These light impulses are received by the light receptor and then transmitted by light transmitter. Generally, information can be transmitted over four optical channels, two ways each. The speed depends on what optical receiver/transmitter is used.

Third concept: Radio waves

In this concept, radio waves are used. These waves can transmit data from one module to another module. Data can be received by radio receptors and radio transmitters can transmit data.

Fourth concept: CAN-bus (Controller area network)

This concept is now used in the connector design. It is a simple two-wire differential serial bus system. It can operate in noisy electrical environments with a high level of data integrity. It is capable of high-speed (1 Mbits/s) data transmission over short distance (40 m). CAN-bus is highly fault tolerant, with powerful error detection.

Step 3: Concept Combination Matrix

There are four main functions for designing of the connector for the self-reconfigurable modular serpentine sensing robot. Each function has different concepts. The function 1 has eight concepts. The function 2, the function 3, and the function 4 have four, six, and four concepts respectively. Therefore, the total number of concepts in these four functions is 8+4+6+4=22. The concept combination of these four functions, i.e., each concept from each function, has created the concept combinations solution. The total number of concept combination solutions is 8*4*6*4 =768. It is very difficult to manage a big number of concept combination solutions. Therefore, a square matrix was created to reduce the concept combination solutions. The square matrix allows a comparison of concepts by graphing the various combinations of functions. The concepts have been placed in rows and columns in this square matrix. The concept of one function has been compared with the concepts of other functions. These concepts are evaluated (compared) using a number system. A concept that works is indicated with +1. Concepts that do not work are indicated with a 0 or -1. For example, the arm (row 7) of the function 1, +1 relation with the clutch (row 13) of the function 2 means that this combination works. Finally, matrix 1 (Table 13) and matrix 2 (Table 14) shown below have been developed with the same rule.

Table 13: Concept combination matrix 1

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Ball joint	1	x																					
Lamella	2	xx	x																				
S-type	3	xx	xx	x																			
Blade	4	xx	xx	xx	x																		
Chennel	5	xx	xx	xx	xx	x																	
Magnetic	6	xx	xx	xx	xx	xx	x																
Arm	7	xx	xx	xx	xx	xx	xx	x															
Lock	8	xx	xx	xx	xx	xx	xx	xx	x														
Manual	9	-1	-1	-1	-1	-1	-1	-1	-1	x													
Magnet	10	1	1	1	1	-1	1	-1	-1	x	x												
Sensing	11	1	1	0	1	-1	0	-1	-1	x	x	x											
Rack	12	0	0	0	0	1	-1	1	1	x	x	x	x										
Spring	13	1	1	1	1	0	1	0	0	1	1	1	0	x									
Plug	14	0	0	0	0	0	0	0	0	0	0	0	0	xx	x								
Coil	15	0	0	0	0	0	-1	-1	0	0	0	0	0	xx	xx	x							
Electrode	16	1	1	1	1	0	1	0	0	1	1	1	0	xx	xx	xx	x						
Clutch	17	0	0	-1	0	1	0	1	1	0	1	0	1	xx	xx	xx	xx	x					
Conducti	18	1	1	1	1	0	1	0	0	1	1	1	0	xx	xx	xx	xx	xx	x				
IR	19	0	0	0	0	1	0	1	1	0	1	0	1	0	1	1	0	1	0	x			
Optical	20	1	1	1	1	0	1	0	0	1	1	1	0	1	0	0	0	0	0	xx	x		
Radio	21	0	-1	-1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	xx	xx	x	
CAN	22	1	1	1	1	0	1	0	0	1	1	1	0	0	0	0	1	0	1	xx	xx	xx	x
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22

Table 14: Concept combination matrix 2

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Ball joint	1																						
Lamella	2																						
S-type	3																						
Blade	4																						
Chennel	5																						
Magnetic	6																						
Arm	7																						
Lock	8																						
Manual	9	-1	-1	-1	-1	-1	-1	-1	-1														
Magnet	10	1	1	1	1	-1	1	-1	-1														
Sensing	11	1	1	0	1	-1	0	-1	-1														
Rack	12	0	0	0	0	1	-1	1	1														
Spring	13	1	1	1	1	0	1	0	0	1	1	1	0										
Plug	14	0	0	0	0	0	0	0	0	0	0	0	0										
Coil	15	0	0	0	0	0	-1	-1	0	0	0	0	0										
Electrode	16	1	1	1	1	0	1	0	0	1	1	1	0										
Clutch	17	0	0	-1	0	1	0	1	1	0	1	0	1										
Conducti	18	1	1	1	1	0	1	0	0	1	1	1	0										
IR	19	0	0	0	0	1	0	1	1	0	1	0	1	0	1	1	0	1	0				
Optical	20	1	1	1	1	0	1	0	0	1	1	1	0	1	0	0	0	0	0				
Radio	21	0	-1	-1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0				
CAN	22	1	1	1	1	0	1	0	0	1	1	1	0	0	0	0	1	0	1				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22

Combination of different concept solutions

After developing matrix 1 and matrix 2, all concept solutions are combined for making decision for the final concept solution. The concept solutions are combined where the values of comparisons are all (+1). One concept was taken from function 1 and then that concept was combined with other (+1) concepts of other functions and developed Table15. For example, the ball joint has a better relation with the magnet and sensing than with the rack and manual concept.

Table 15: Solutions of different combinations of different concepts

Concept Solutions Number	Connection Module	Auto/Mech connection	Transfer power	Transfer data
1	Ball joint	sensing	Conductive	CAN
2	Ball joint	sensing	Electrode	CAN
3	Ball joint	sensing	Spring	Optical
4	Ball joint	Magnet	Conductive	CAN
5	Ball joint	Magnet	Electrode	CAN
6	Ball joint	Magnet	Spring	Optical
7	Lamella	sensing	Conductive	CAN
8	Lamella	sensing	Electrode	CAN
9	Lamella	sensing	Spring	Optical
10	Lamella	Magnet	Conductive	CAN
11	Lamella	Magnet	Electrode	CAN
12	Lamella	Magnet	Spring	Optical
13	S-Type	Magnet	Conductive	CAN
14	S-Type	Magnet	Electrode	CAN
15	S-Type	Magnet	Spring	Optical
16	Blade	sensing	Conductive	CAN
17	Blade	sensing	Electrode	CAN
18	Blade	sensing	Spring	Optical
19	Blade	Magnet	conductive	CAN
20	Blade	Magnet	Electrode	CAN
21	Blade	Magnet	Spring	Optical
22	Channel	Rack	Clutch	IR
23	Magnetic	Magnet	Conductive	CAN
24	Magnetic	Magnet	Electrode	CAN
25	Magnetic	Magnet	Spring	Optical
26	Arm	Rack	Clutch	IR
27	Lock	Rack	Clutch	IR

Step 4: Pugh decision matrix method

This is the last step for making the final decision for the design concept by using the Pugh decision matrix method. This Pugh decision matrix method is a good solution method for obtaining the final solution. Usually the designer has a favorite design. This concept solution can be used as a base (datum). Each of the customer requirements has compared all other concept solutions with the base solution. For comparison, the concept solution was evaluated as being better (+1), the same (0), and worse (-1). Table 16 was developed after using this method. A total of twenty-seven concept solutions remained after eliminating 768 original concept solutions. The best solution has come after evaluating the total value of each concept solution. The total value of each concept solution is the sum of the product of weighted value and evaluated value for each customer requirement.

$$\text{Total value} = \sum (\text{weighted value})^* (\text{evaluated value})$$

For example, concept solution number 7, lamella, is the concept of function 1. Sensing, conductive and CAN are the concepts of function 2, function 3, and function 4 respectively. The total value of this concept solution is - 0.31. This is not good, in respect to the connection mechanism, but good for mechanical forces transmission.

$$\text{Total value} = (0.41)^*(-1) + (0.29)^*(0) + (0.15)^*(0) + (0.10)^*(+1) + (0.05)^*(0)$$
$$= (-0.31)$$

Table 16: Estimations of various solutions by using Pugh matrix

Sl. Number	Connection Mechanism	Transfer of Power	Transfer of Data	Transfer of Mechanical Forces	DOF	Total
	Weighted 0.41	Weighted 0.29	Weighted 0.15	Weighted 0.1	Weighted 0.05	
1	0	0	0	0	0	0
2	0	-	0	0	0	-0.29
3	0	-	-	0	0	-0.44
4	-	0	0	0	0	-0.41
5	-	-	0	0	0	-0.70
6	-	-	-	0	0	-0.85
7	-	0	0	+	0	-0.31
8	-	-	0	+	0	-0.60
9	-	-	-	+	0	-0.75
10	-	0	0	+	0	-0.31
11	-	-	0	+	0	-0.60
12	-	-	-	+	0	-0.75
13	-	0	0	-	0	-0.51
14	-	-	0	-	0	-0.80
15	-	-	-	-	0	-0.95
16	0	-	0	+	0	-0.19
17	0	-	0	+	0	-0.19
18	0	-	-	+	0	-0.34
19	0	-	0	+	0	-0.19
20	0	-	0	+	0	-0.19
21	0	-	-	+	0	-0.34
22	-	0	-	+	0	-0.46
23	-	0	0	-	0	-0.51
24	-	-	0	-	0	-0.80
25	-	-	-	-	0	-0.95
26	-	0	-	-	0	-0.66
27	-	0	-	-	0	-0.66

The total value of concept solutions lies between zero and negative 0.95. In this Pugh decision matrix method, the first concept solution has a maximum value, of zero. Therefore, the first concept solution is a better solution for design of the connector for the self-reconfigurable modular serpentine sensing robot.

Final solution:

This design solution is a combined idea from different fields (taken from literature) and generated a unique idea for this design.

Function 1: Connect module

Ball-Socket joint: The male and the female part are the main parts of this joint. The male part has a target ball, and the female part has a cup shaped socket with alignment cone. This alignment cone guides the target ball and tolerates significant amount of initial misalignment. The target ball is inserted in the cup shaped of the socket and the target ball is stopped in the cup and locked by the spring-loaded locking balls. There are three numbers of spring-loaded locking balls used for locking purpose. The locking spring and locking ball are welded together. The other end of the spring is welded with the block that is placed at end of the cylindrical channel. The top portion of the teeth of the male and the female part are curve shaped so that they can mesh easily.

Function 2: Automatic/Mechanical connection- Sensing system

Function 3: Power transfer

Male and female conductive materials: In this system, the power is transmitting into male and female part by conducting materials. However, the power is transmitted only when the male and female part are coming to each other. The sensing system is used for this purpose.

Function 4: Data transfer- CAN-bus

4.4 Diagram of design concept of connector for self-reconfigurable modular serpentine sensing robot

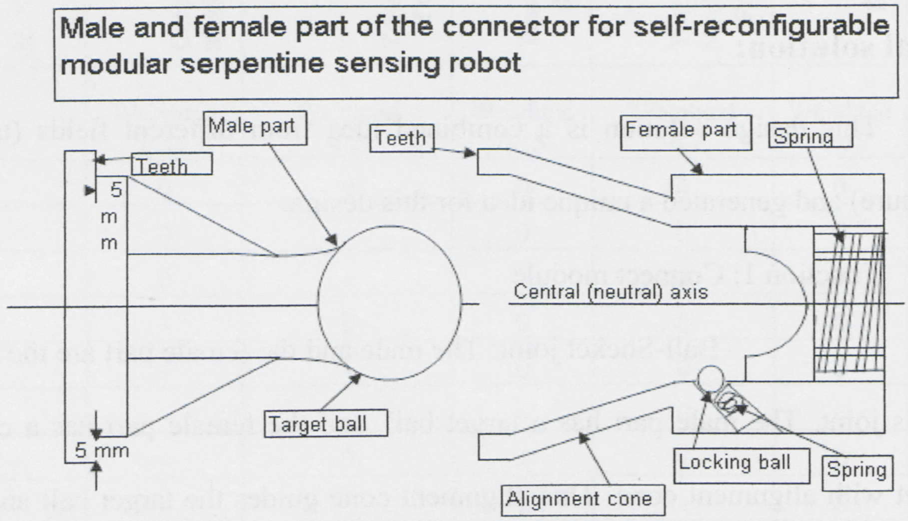

Fig 60: A diagram of connector for self-reconfigurable modular serpentine sensing robot

This is a design concept for the design of the connector for the self-reconfigurable modular serpentine sensing robot (refer to Fig 60) and it is a combination of different ideas in a unique way. The main requirements are connection mechanism, transfer of power, transfer of data, transfer of mechanical forces, and DOF. In this final design concept, the connection mechanism is the ball and socket joint concept. The outside portion of the target ball contacts the inside portion of the female part and power is transmitted by the conductive method. Data is transferred through the CAN method. The stress analysis is done to feasible of the design for transmitting of the mechanical forces. Fig 61 shows the detail drawing of the design of the connector.

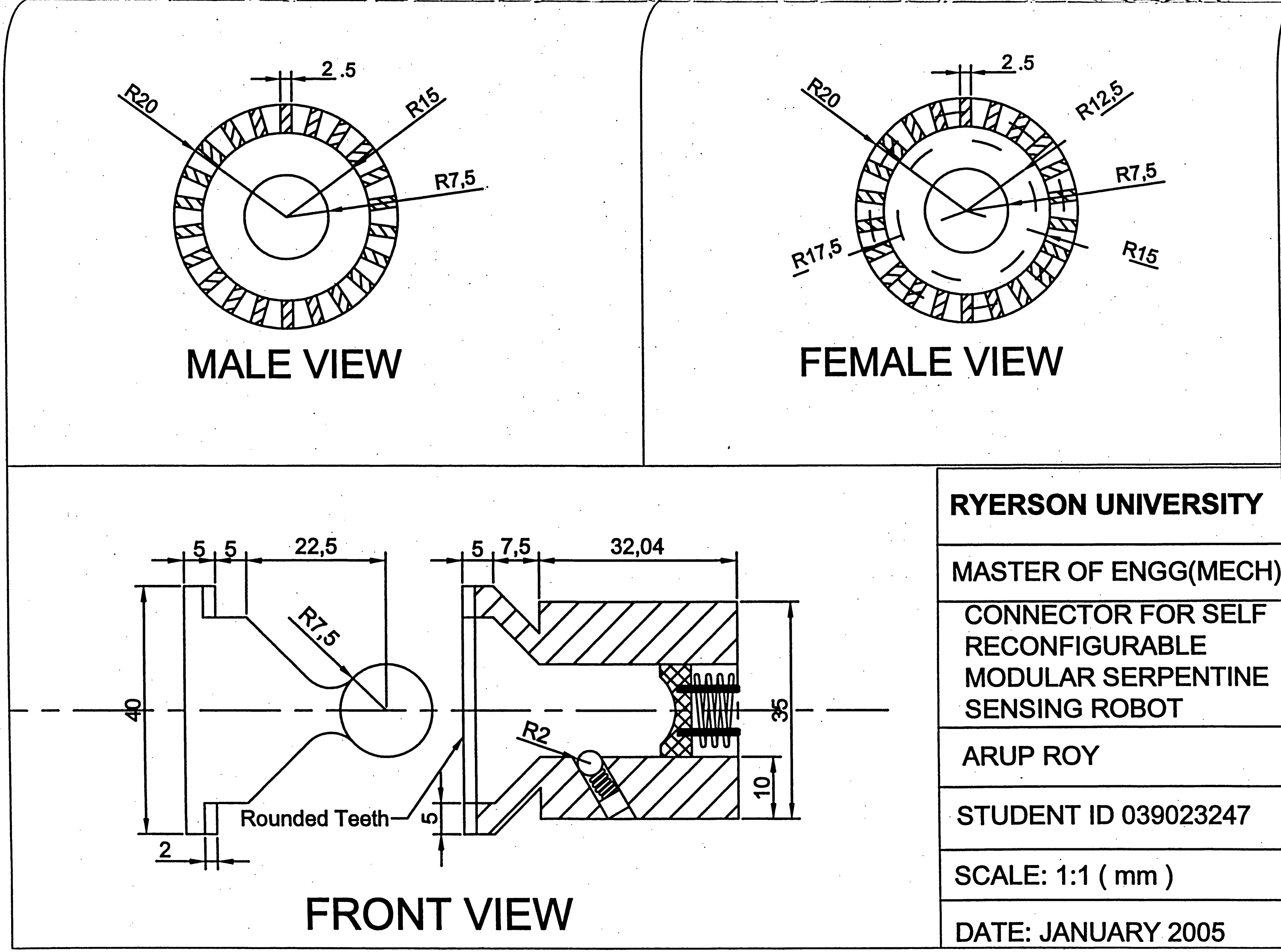

Fig 61: A CAD DRAWING

4.5 Force and stress analysis

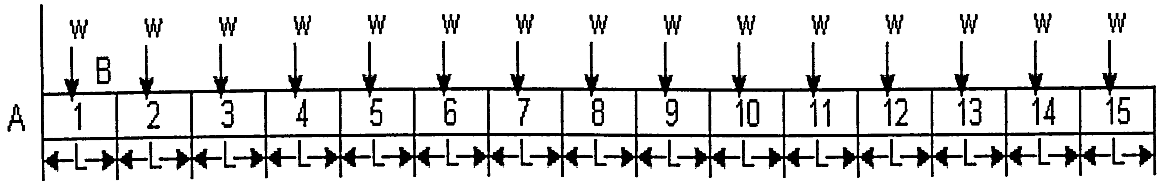

Fig 62: Force and stress analysis

The above design of the connector is a concept of different functions. However, this design will not be accepted without the feasibility study of the design from a stress point of view. For this reason, the maximum amounts of forces are calculated on the base joint due to its own weight. This study is considered two worst-case configuration scenarios that generate the maximum stresses at the base joint of a self-reconfigurable modular serpentine sensing robot. These two worst-case scenarios are: for compressive stress due to bending moment (Case-1), and shearing and compressive stress due to twisting torque (Case-2) (refer to Fig 62 and Fig 63). Case-1, the self-reconfigurable modular serpentine sensing robot is fully extended horizontally and the base connector has to cantilever the rest of the body of the robot. Case-2, the base joint is loaded with maximum twisting torque at the time when the serpentine is in an 'L' shape configuration. All dimensions are taken from Table-1.

n = total number of modules of this robot = 15

L = the length of the module = 5 cm = 0.05 m

m = total mass of the module= 200 gm = 0.2 kg

w = weight of the module (mass*g) = (0.2 * 9.81) kg- m/ s^2 = 1.96 N

$g = 9.81\ m/s^2$, $1\ kg\text{-}m/s^2 = 1\ N$

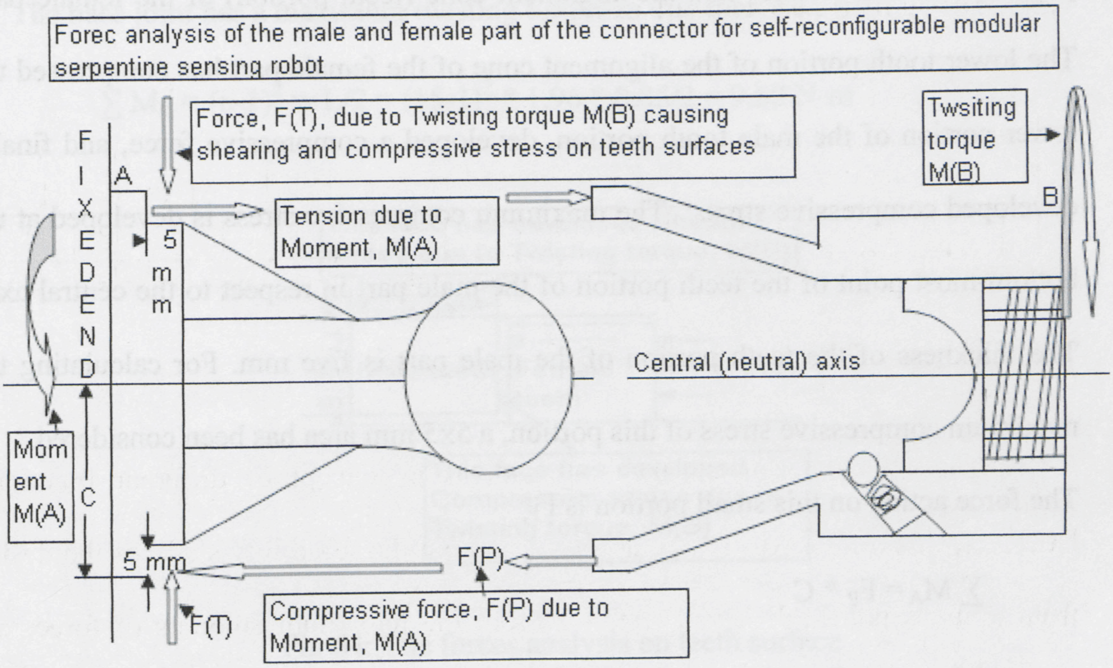

Fig 63: A detail diagram force and stress analysis

Case-1

Total Moment at the point 'A',

$$\sum M_A = w[\,(14L+L/2) + (13L+L/2) + (12L+L/2) + (11L+L/2) + (10L+L/2) + (9L+L/2) + (8L+L/2) + (7L+L/2) + (6L+L/2) + (5L+L/2) + (4L+L/2) + (3L+L/2) + (2L+L/2) + (L+L/2) + (L/2)\,] = 112.5\ w\ L = n^2\ w\ L/2$$

$$\sum M_A = (15)^2 * 1.96 * 0.05/2 = 11.04\ N\text{-}m$$

The bending moment (M_A) is the maximum at the point A, due to the weight of the modules from the base module. Matching teeth and the ball and socket portion connect the male and female parts of this connector. The different forces are mainly acting on the teeth portion of the male and female parts. The compressive and tensile forces F_P, due to the bending moment (M_A), are developed on the male part (teeth portion) of the connector and the alignment cone (teeth portion) of the female part. The lower tooth portion of the alignment cone of the female part has compressed the lower portion of the male tooth portion, developed a compressive force, and finally developed compressive stress. The maximum compressive stress is developed at the bottom-most point of the teeth portion of the male part in respect to the central axis. The thickness of the teeth portion of the male part is five mm. For calculating the maximum compressive stress of this portion, a 5x5 mm area has been considered. The force acting on this small portion is F_P,

$$\sum M_A = F_P * C$$

M_A = Bending moment at point A (maximum), C = Distance from the neutral axis to the bottom most point, a = area of the small block (5x5 mm) of the lower portion of the male part (teeth).

$M_A = 11.04$ N-m.

$C = 0.02$ m.

$a = 5 * 5 \text{ mm}^2 = 25 * 10^{-6} \text{ m}^2$

$F_P = \sum M_A / C = 11.04 / 0.02 = 551.81$ N

$$\text{Compressive stress due to bending moment} = \frac{F_P}{a} = \frac{551.81}{25 * 10^{-6}} \text{ N/m}^2$$

$$= 22.07 \text{ MPa}$$

Case-2

The base joint has a maximum twisting torque in this case, i.e.,

$$\sum M_B = (n-1)^2 \, w \, L/2 = (15-1)^2 * 1.96 * 0.05/2 = 9.60 \text{ N-m}$$

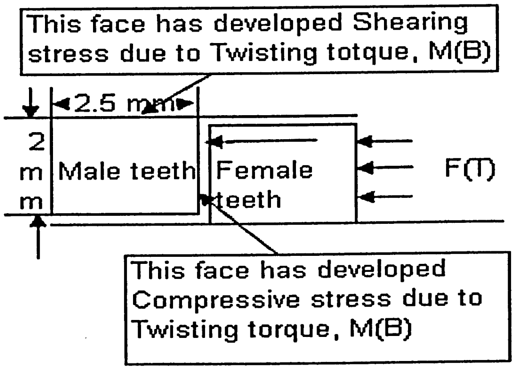

Fig 64: The forces analysis on teeth surface

The force (F_T) is acting on the teeth surface of the male and female parts and developed shearing and compressive stresses (refer to Fig 64). C is the distance from the central (neutral) axis, a_{tc} is the teeth area for compression and a_{ts} is shearing.

$$\sum M_B = F_T * C$$

$$F_T = \sum M_B / C = 9.604 / 0.02 = 480.20 \text{ N.}$$

Teeth dimension = 2.5 x5 x 2 mm (width x length x height)

$a_{tc} = 2 \times 5 \text{ mm}^2 = 10 \times 10^{-6} \text{ m}^2$, $a_{ts} = 2.5 \times 5 \text{ mm}^2 = 12.5 \times 10^{-6} \text{ m}^2$,

Number of teeth = 22.

Total $a_{tc} = 22 \times 2 \times 5 \text{ mm}^2 = 220 \times 10^{-6} \text{ m}^2$,

Total $a_{ts} = 22 \times 2.5 \times 5 \text{ mm}^2 = 275 \times 10^{-6} \text{ m}^2$,

$$\text{Compressive stress due to twisting torque} = \frac{F_T}{a_{tc}} = \frac{480.20}{220x10^{-6}} \text{ N/ m}^2$$

$$= 2.18\text{MPa}$$

$$\text{Shearing stress due to twisting torque} = \frac{F_T}{a_{ts}} = \frac{480.20}{275x10^{-6}} \text{N/m}^2$$

$$= 1.75 \text{ MPa}$$

Assuming that stainless steel is used for this connector, the tensile, compressive, and shearing stresses of the stainless steel are 515-827, 207-552, and 171-275 MPa respectively. The calculated stresses of this connector are lower than allowable stresses of stainless steels. Therefore, the design is safe. All calculated stresses are within the limit of the stresses of stainless steels. Therefore, safety factor more than 10 can be used for this design.

The force and stress calculations in this study are in the primary stage, only bending and twisting torque due to its weight has been considered. The dimensions of different parts of this connector are all approximations. The different types of force analysis of different loading conditions, using FEA and many optimizations will be needed for optimization of the all dimensions and to make a model in future.

Chapter 5

Conclusion

The locomotion of self-reconfigurable modular robots in a real world environment is the highest challenge accepted by researchers. The cost of production is another key area to be looked upon if society wants to derive the real benefit of this advanced technology. The first portion of this study has attempted to depict a brief picture of the different types of self-reconfigurable modular robots, their connectors, and their different applications. A remarkable development in this field has taken place over the years. In order to achieve more reliable and efficient self-reconfigurable robots, more research is needed in the areas of hardware and control. The connectors play a vital role in the self-reconfigurable process and hence, more thrust should be given in the design of fault minimizing and robust connectors. This project has used QFD and Pugh decision matrix methods for developing the design of a connector for a self-reconfigurable modular serpentine sensing robot. This connector can transmit mechanical forces, torques, power, and data to neighborhood modules. The main parts of the connector are male and female and these parts are made of stainless steel. A force and stress analysis was done to determine the safety factor.

A future direction of research is the use of advanced technology, such as micro fuel cells or wireless energy supply for reconfiguration and locomotion. Future work also includes sensor networking that allows a large number of distributed nodes to select a task from many alternatives.

The future generation of self-reconfigurable robots will have additional improvement to the mobility, communications and sensing capabilities. These will help in a wider variety of information retrieval and wider team dispersal.

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Appendix

Table 1: Advantages and Disadvantages of Connectors

CONNECTORS	ADVANTAGES	DISADVANTAGES
1. DRAGON	GEOMETRY: STRONG, SIMPLE, SYMMETRY, GENDER-LESS, SELF-ALIGNMENT IN 5 DOF ($\pm$15 MM, $\pm 45^0$) LATCHING: SIMPLE LATCH ACTUATORS, LOW POWER CONSUMPTION & NO CONSUMPTION IN STATIC STATE, HIGH LATCH LOAD & IMPACT STRENGTH ROBUSTNESS: IMPACT & LOAD STRENGTH, STIFFNESS ENERGY TRANSFER: POWER & SIGNAL, RATE & RELIABILITY MAINTENANCE: FEW MOVING PARTS, EASY ACCESS WEIGHT: 170 GMS, LOADING CAPACITY: 70 KG.	
2. NOVEL SMART	GEOMETRY: GENDERED, MECHANICAL &/OR ELECTRICAL CONNECTIONS, ONE OR MULTIPLE PIN FEBRICATIONS, OUTSIDE DIAMETER OF THE PLUG FINGER 1.1 INCHE AND THICKNESS 0.11 8 INCHE. OUTSIDE DIAMETER OF THE RECEPTACLE FINGER 1.417 INCHE AND THICKNESS 0.058 INCHE. TYPE OF OPERATIONS: FULLY AUTOMATIC OPERATION, MANUAL OPERATION AND MANNUAL AND AUTOMATIC EMERGENCY ACCESS FROM OUTSIDE LATCHING: SELF-LATCHING MECHANISM ROBUSTNESS: STRONG AND RELIABLE. ENERGY TRANSFER: TRANSMISSION OF AXIAL FORCE, SHEAR FORCE AND TORQUE . PARTS: TWO PARTS , PLUG (MALE) AND RECEPTACLE (FEMALE), WEIGHT: NA LOADING CAPACITY: NA APPLICATION: IN MODULAR ELECTROMECHANICAL SYSTEM IN SPACE AND AEROSPACE INDUSTRY, SMART SEATBELTS FOR CARS AND AIRPLANES.	FOR DISCONNECTION PLUG MUST TRAVEL GREATER OR EQUAL TO THE WIDTH OF SHOULDER OF RECEPTACLE.
3. CONRO	GEOMETRY: SYMMETRIC, HOMOGENEOUS, SELF-SUFFICIENT, AUTONOMOUS , MINIATURE, COMPACT LATCHING: EASY TO CONNECT AND DISCONNECT, ENERGY CONSUME AT THE TIME OF DELOCKING ROBUSTNESS: ROBUSTAND RELIABLE, EFFECTIVE ENERGY TRANSFER: ENERGY EFFICIENT MAINTENANCE: WEIGHT: LOADING CAPACITY: APPLICATIONS: USED AS THE RESEARCH PLATFORMS FOR BOTH DISTRIBUTED AND CENTRALISED ROBOT CONTROL	
4. POLYBOT	GEOMETRY: G3: CUBIC 5 CM, IDENTICAL, HERMAPHRODITIC AND 4-WAYS ROTATIONAL SYMMETRY, 1 DOF, CONNECT MODULES OF SAME PLANE AND OUT-OF-PLANE, LATCHING: DOCKING PROCESS BY MECHANICAL AND DISCONNECTED BY SMA ACTUATOR ROBUSTNESS: STRONG AND RELIABE ENERGY TRANSFER: PHYSICALLY AND ELECTRICALLY, TORQUE TRANSMIT 1 NM MAINTENANCE: WEIGHT: 70 GMS LOADING CAPACITY: APPLICATIONS: CONSTRUCTION, SPACE MANIPULATION, SURFACE MOBILITY	

5. PASSIVE & ACTIVE	PASSIVE: GEOMETRY: SYMMETRIC, CUBIC (SIDE 2.54 CM), ROTATION AT 60° ANGEL TO BOTH LEFT & RIGHT DIRECTIONS LATCHING: SERVES AS NEGATIVE CONTACT, KEEPS BATTERY IN PLACE. ROBUSTNESS: STRONG AND RELIABLE ENERGY TRANSFER: EFFICIENT ENERGY TRANSFER USING 14 PINS. PARTS: NO MOVING COMPONENTS, WEIGHT: 30 GMS (WITH BATTERY 8GMS) LOADING CAPACITY: NA ACTIVE: GEOMETRY: SYMMETRIC,, CUBIC (SIDE 2.54 CM), ROTATION AROUND PITCH AXIS, LATCHING: HELPS IN DOCKING PROCESS, LOCKING MECHANICAL AND DELOCKING ELECTRICAL ROBUSTNESS: STRONG AND RELIABLE ENERGY TRANSFER: EFFICIENT ENERGY TRANSFER PARTS: TWO PARTS (AN ARM & A FACE) WEIGHT: 15 GMS LOADING CAPACITY:NA	CAN CONNECT MODULE ONLY IN THE SAME PLANE. HIGH POWER COSUMPTION AT THE TIME OF DISCONNECTION. MODULE CAN NOT WORK MORETHAN 45 MINUTES AND CAN NOT LIFT MORE THAN ONE IDENTICAL MODULE
6. CHANNEL & KEY	GEOMETRY: 3 DOF, RIGID, CONNECTION MECHANISMS ARE MISALIGNMENT TOLERANT AND CORRECTING LATCHING:LOCKING MECHANICAL, DELOCKING ELECTRICAL ROBUSTNESS: RELIABLE ENERGY TRANSFER:POWER MAINTENANCE: WEIGHT: LOADING CAPACITY:	NOT FLEXIBLE
7. 3-D	GEOMETRY: GENDER-LESS, CUBIC, POWERFUL, 12 DOF(6 DOF FOR ARM CONNECTION & 6 DOF FOR ARM ROTATION), SIMPLE & COMPACT, UNIQUE DESIGN, EASY TO HAVE DIFFERENT CONFIGURATION. LATCHING: LOCKING & DELOCKING MECHANICAL (THROUGH ELECTROMAGNETIC CLUTCH). ROBUSTNESS: STRONG AND VERY RELIABLE ENERGY TRANSFER: POWER & INFORMATION TRANSMISSION MAINTENANCE:SELF-ASSEMBLY & SELF REPAIR WEIGHT: LIGHT WEIGHT & SMALL IN SIZE PARTS: THREE- HAND HEAD & CUFF. LOADING CAPACITY: LIFTS UNIT AGAINST GRAVITATIONAL FORCE.	
8. LINK & JOINT	GEOMETRY: GENDERED, SIMPLE, 1 DOF, CUBIC, RIGID, CONNECTED ON THE BASIS OF BUILDING BLOCK PRINCIPAL LATCHING: MECHANICAL ROBUSTNESS: RELIABLE ENERGY TRANSFER: POWER MAINTENANCE: SIMPLE WEIGHT:	
9.INTEGRATED QUICK-COUPLING	GEOMETRY: GENDERED, EASY CONNECTION LATCHING: LOCKING & DELOCKING MECHANICAL ROBUSTNESS:HIGHLY RELIABLE ENERGY TRANSFER: POWER & SIGNALS MAINTENANCE:SIMPLE WEIGHT:	MANNUAL CONNECTION

POWER EFFICIENT: A ROBOT HAS A VERY LIMITED ON-BOARD POWER SUPPLY.
RELIABLE: CONNECTIONS MUST ENDURE VARIOUS OPERATIONS.
COMPACT: THE MECHANISM MUST FIT INTO A TIGHT SPACE.
FLEXIBLE TO OPERATE: EASY TO CONNECT AND DISCONNECT.
HETEROGENOUS: SOME MODULES ARE DIFFERENT FROM OTHERS.
HOMOGENOUS: ALL MODULES ARE IDENTICAL.

Table 2: Modules size and weight

Robot	Size (LxBxH) mm	Weight (gm)
G-3	50x50x45	200
Conro	L= 108	115
Crystalline	4x4x7 inchs	12 ounces
Fractum	265x265x265	7000
Micro	4x4x8	80
Rikan	L=90	600
Telecube	6x6	30
Molecule	4x4x4 inch	1400
MTRAN	6x6x6	400
I-cubes	L= 80	370
Connector	**Connector-size**	**Connector- Weight**
Diagon	Outer dia=75 mm	170 gm
Telecube	Square, 3.6mm thick	160 gm
Active and passive	Cube 2.54 cm	15 gm