A Smart Micro Factory Design: An Integrated Approach

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Abstract: Smart factory research is paced up in the current decade due to the development of many enabling technologies and tools available to the developers. This has led to the progress of cyber physical systems in manufacturing, now coined as cyber physical production systems. The ultimate goal of this domain is to integrate underlying technologies and connect physical plants with the virtual factory in real time for improvement in product quality, process improvements, predictive maintenance, mass customization as well as mass production. The involved technology modules include sensor network, machine learning and AI, Internet of things, human machine interface, augmented reality and collaborative robotics. For the physical element in this research, a micro factory scenario is envisaged that consists of a high precision micro/nano positioning stage installed on a tabletop sized conventional machine tool, a collaborative robot for handling of micro parts and running of machine operations, other factory devices and a human worker for supervision tasks. Due to the multi-faceted technologies involved in both the virtual and physical systems, a simultaneous design strategy is followed in both domains. First, a flexure based micro positioning, 3-axis stage device is designed that can be installed on a conventional 3-axis desktop size milling machine. Secondly, a work zone is considered for effective human robot collaboration in the production area. The work zone considered as a social space is designed in a safe and secure way with the help of integrated devices, IoT and AI.

1   **Introduction**

High productivity and high flexibility are the demands of digital manufacturing industry. The current trend in manufacturing came up with fourth industrial revolution i.e. industry 4.0 [1]. The concept is taking into its shape from automated manufacturing systems to intelligent manufacturing systems but still in its nascent stage. One of the basic components of these systems is cyber physical system (CPS) [2] i.e. a mechanism controlled by computer based algorithms integrated with users over a network. The CPS is the smart system that consists of physical and computational elements, these elements can be distributed into four layered architecture, which are sensing layer, networking layer, analysing layer and application layer [3]. The benefits of these systems are time saving and flexibility; feasible for even a demand of quantity one placed by an individual customer, this does not require reconfiguration of the manufacturing system. The term CPPS (cyber physical production systems) was coined in Germany that proposed a complete automated system in the realm of industry 4.0; a manufacturing system based on cyber physical system that comprises of physical elements which are robots, conveyors, sensors, actuators etc. and a cyber-layer based on computational elements [4]. The independent elements of CPPS can cooperate with each other through internet of things (IOT) [5] a concept in which components having unique identity can transfer data to each other over a network without requiring any human-computer interaction thus creating smart factories [6]. Internet can be one such communication protocol in IOT. A similar case of smart factory

production system is presented in [7]. Though the robots and computers take a major share in the CPS, however human presence is essential for productivity either for supervision or complicated jobs that robots cannot undertake. The smart factory concept exists for large production systems however there is very little research that exists for manufacturing at micro domain which is deemed necessary due to the limitations of the macro devices i.e. their large size, more power consumption, large cost effect, they are more susceptible to environment conditions and their control loop is believed to be significantly larger [8]. In this chapter a smart factory is proposed; the collaboration is envisaged between a human, a cobot and a multi-staged micro milling machine. The related concepts are stated below:

1.1   **Industry 4.0**

The latest trend of automation in manufacturing technologies incorporating data exchange is referred to as Industry 4.0. The concept suggests the use of Internet of things, cyber-physical systems, cognitive computing and cloud computing [9]. The modernization of industry starts with the use of steam for mechanization when first machines were built; that was the first era of modern industry. Then with the advent of electricity, the machines were built which came up with the concept of mass production and later the assembly lines were built; the second era. Then the digital world came into being which brought logic and control in the industry; the incorporation of computers came up with the beginning of automation, where machines and later robots replaced human workers on the assembly lines; the third era of industrial modernisation. And presently we are entering into an era known as Industry 4.0 (the fourth industrial revolution), in which remotely placed robots and machines are connected to AI feed computers that can control them with very little human interference. The interaction between operators, robotics and computers come together in an entirely new way in which machine learning

algorithms are used to learn and then control the process [10]. The term Industry 4.0 was originally conceived in the context of manufacturing; however the concept evolved with the passage of time. Different industrial, governmental and academic collaborations now fall under the scope of Industry 4.0 which led to a new term 'Industrie 4.0'.   But still in the broader context the Industry 4.0 is only about manufacturing which incorporates smart factories and processes/activities/technologies related to production and the areas related to them. Also the Industry 4.0 is not merely related to some group of technology like Internet of Things (IoT). It can be related to production, servicing, consumer interaction/feedback. This improves upon cost and quality which can be attained by acquiring real-time data, cutting the inefficiencies and removing irrelevance in this customer-centric environment where the value is speed, cost effectiveness and value-added innovative services. The concept is also related to improvement in digital supply chain model. In the other sense it means that this term actually benefit business models with the use of innovation while transforming business models and processes. The benefits are profit, decrease cost, enhanced customer relationship and optimized lifetime value; in short increase in customer loyalty. Another aspect is in terms of flexibility i.e. to sell more and innovate products in order to grow and remain relevant; this would be due to customer demand or to be part of the top most service/product or low-margin commoditized services/products or the services/products/solution that will disappear shortly due to 'digital disruption' [11].

1.2   Internet of Things

A system in which a large number of embedded devices when communicate with each other through Internet protocols is termed as "Internet of Things" (IoT). Because of the use of internet, these devices are also called "smart objects,''. These devices spread over the

environment and are not directly operated by humans, for example some components in vehicles or buildings not necessarily taking commands through human operator. The Internet of Things provides a concept in which network connectivity is extended up to everyday items, objects, and sensors. The computing capability embedded into these systems not necessarily a central computer let these devices to consume, generate and exchange data; this all is done with minimal human intervention. The implementation of Internet of Things is done through different models of communications, each having unique characteristics. Internet Architecture Board presented four common models: Device-to-Device, Device-to-Gateway, Device-to-Cloud and Back-End Data-Sharing. The variance in these models provides the flexibility in terms of connectivity and value to the users provided by the IoT devices [12]. The devices in the Internet of things not only include traditional PCs and mainframes but also refers to a worldwide network of devices like smartphones, embedded sensors, appliances, wearables (e.g. health sensors, smart watches) all outfitted with internet protocol (IP) connectivity. It can be the connectivity of machines and electronic devices via a network that could be Wi-Fi or Ethernet. The transmission/reception of data could be direct amongst each other or from the cloud. In a manufacturing industry scenario the machines, the devices and the actuators, embedded with sensors, exchange the data directly or through a central computer over a wired/wireless network using the same internet protocol (IP) [13]. The examples of IoT technologies which can be used in manufacturing industry are wireless sensor networks (WSN) and other sensor networks that can be used to give information on quantitative/physical properties like materials, work in progress, tooling and finished products. RFID (Radio Frequency Identification) can be used to support production scheduling by capturing the status of the job and overall the performance of the system can be evaluated [14].

1.3 Smart Factories

The smart factory adapts and learns from new demands in which a constant flow of data is coming real time from productions and operations. It represents a way ahead of the existing automated world, where the components are fully connected and the processes are flexible [15]. The integration of data is system wide which contains human operators, physical elements and controlling elements. The aim is to accomplish manufacturing through digitization of processes, keeping track of inventory while providing in process maintenance, inspection or any other type of activity that happens within the entire framework. The outcome expected from this is to provide an agile system that should be more efficient, that can reduce the lead time and must be able to adjust to the unforeseen from within/outside or even predict them, so that a better place is made among the competitive market [16]. The concept of smart factory states that while being flexible it can autonomously run processes of entire production system; the system has the capability to optimize itself, even from a broader network and has a real time/near-real time capability of self-adaptation to changes. Although factories in the past have some degree of automation even few had higher levels, however "automation" the actual term for a smart factory, suggests that the process or task's performance should behave as a single/discrete entity. Old machines which were automated used to take decisions on the basis of linear logic, like turning on/off a motor or opening of valve based on predefined logic. With the advent of artificial intelligence (AI) and then its use in cyber physical systems where physical system and cyber systems are combined, complex decision making processes are introduced in automation to increase optimization in business processes just like humans do. Hence the concept of "smart factory" integrates the decisions taken on the shop floor with the supply chain in the context of a broad enterprise; all this is done through IT/OT connections. This has an effect on the production

by ultimately improving the interaction of customers with suppliers. As this connectivity has changed the manufacturing processes, the emergence of Industry 4.0 (fourth industrial revolution) which suggests the integration of physical and digital entities based on operations technology (OT) and information technology (IT) has also altered the functioning of supply chain. The new concept of *digital supply network* has emerged that shifted from linear operations in sequence to open interconnected operations which has modified the way of competition among the companies. These new concepts demand different capabilities from manufacturers like connected manufacturing systems i.e. vertical integration, myriad operational systems i.e. horizontal integration and end-to-end operations i.e. holistic integration which enhance the organization of complete supply chain [17]. Therefore the new concept of smart factory is a way ahead of traditional automation that has shifted to a flexible and fully integrated system where constant flow of data is coming real time from productions and operations and that can adapt to any unforeseen real time.

1.4   Human Machine Interaction

The interaction between humans and the machines is known as "Human-machine interaction". It is a technical system which is dynamic in nature and accomplishes itself through human-machine interface [18]. The human machine interaction is related to human–computer interaction (HCI) which on the other hand is based on computer technology, it can be said the interaction between human users and computers. This field is not only related to the ways and means that how humans interact with computers but also the novel designing of technologies to let that happen [19]. So in the above context HMI is a multidisciplinary field where research is done on interactions between humans and machines accommodating inputs from Human-

Computer interaction (HCI), exoskeleton control, Artificial Intelligence (AI), Robotics, Human-Robot Interaction (HRI) and Humanoid robots [20].

1.5   Cobots

'Cobot' is a brief abbreviation of a collaborative robot which works in collaboration with a human operator. The cobot manipulate the objects that in turn assist humans, this will be done in accordance with the constraints and guidelines set by the users. These guidelines and constraints can be in terms of virtual surfaces defined by user [21]. The difference between collaborative robots and autonomous industrial robots is that they directly interact with a human operator, sharing the same workspace even payload, whereas autonomous industrial robots remain isolated from humans due to safety issues [22]. This collaboration between the humans and robots is in the revolutionary stage, it is expected that these robots work as companions in line with the humans reading their behaviors and adapt to any changes real time. This is also termed as human-robot collaboration (HRC), the efficiency of HRC depends on effective monitoring of human's actions and the environment, the use of AI to anticipate the actions and state of mind by processing previous knowledge so that likely contribution to the task by human can be ascertained. This type of learning requires robots (cobots) to adapt to variety of humans, different type of human behaviors experienced by them and different human needs. These types of robots are also termed as Social-Cobots, where such adaptation results in more efficient and synchronous working of both the partners, this in terms increase the overall yield of the process [23].

1.6   Micro Systems

The miniaturization of mechanical microsystems is under research that promises to enhance quality of life, health care and economic growth. Understanding of mechanical

properties of materials at micro-scale level is a very important aspect in fabrication of micro devices. The behavior of micro systems not only depends on these properties but another major aspect is the structural geometry of micro systems. Fabrication of micro devices involves special fabrication processes which are widely different from the practices involved in fabrication of macro devices. These are mainly categorized as NLBMM and LBMM techniques. Non-lithography based micro manufacturing (NLBMM) is gaining popularity to make micro 3D artifacts with various engineering materials. Being in the nascent stage, this technology looks promising for future micro manufacturing trends. Applications of these devices are in aerospace, biomedical, consumer products, telecommunication industry and sensors.

1.7 Micro Manufacturing Techniques

Micro-electro mechanical systems (MEMS) technique is one of the most common methods used to manufacture micro devices. These techniques use silicon based semi-conductor processing technology for large batch production, where photo-etching is used to shape silicon wafers using chemical and dry processes. Various other commercially viable techniques are also researched for fabrication of micro devices like ultrasonic, micro-electro discharge machining methods, photo-lithography, laser and ion beam. Majority of these processes are slow, only viable for materials based on silicon, cater for planar shapes, their inability to manufacture in small batches (customization) and are less cost effective [24].

1.8 Micro-Mechanical Machining

Micro-mechanical machining is one of the latest techniques for fabricating micro devices. The size range of these components can vary from tens of micrometers to a few millimeters. The advantages of this technique are that it bridges the gap between macro-domain and the 3D structures of nano/micro domains, lithographic methods that are very expensive are no more

required, they are suitable for accommodating individual components and monitoring of in-process quality of components [25]. Two types of micro machine tools are found mainly i.e. precision machines and miniature machines. The characteristics of precision machine tool are a large foot print, high rotational speed of the spindle to decrease chip removal rate, use of air bearing/air turbines that allow low torque operations, linear drive motors and a large control system. Whereas the characteristics of miniature machines tools are their cost-effectiveness, they have higher natural frequencies due to substantially smaller mass, they produce low vibration amplitudes and the portability of these systems is easy thus making them beneficial. The actuators used in micro-machine actuators are either voice coil actuators or flexure based piezoelectric designs [24].

1.9   Micro Factory

A micro factory is a factory of miniature size whose products are also of small dimensions. This name was coined in 1990 by Mechanical Engineer Laboratory (MEL) of Japan [26]. Requirements emanated from agile and flexible manufacturing, cost effectiveness, technology and environmental issues demand greater challenges and competition from manufacturing industry in borderless business. As the parts used in latest gadgetries are becoming smaller, still the machine tools in practice are of conventional size, lacking justification. Reduction in the size of manufacturing systems can accrue many benefits like reduction of space, cost effectiveness, energy consumption, smart solutions, better environmental conditions and low initial investment. This will have overall effect on agility in manufacturing industry as the factories can be reconfigured easily. Furthermore, the portability of the machine tools will be very easy, eliminating their requirement of fixture at factory. They can be even placed at manufacturing laboratories, offices, classrooms or even in living areas. One of the

major advantages of the micro factory despite saving materials, space and energy is saving time especially in reconfiguration [27]. To achieve this advantage, full automation is one of the major requirements of micro factories that demands fully automated machine tools, in process automatic inspection, automated assembly lines, automated material feeding/waste removal systems, tool replacement and evaluation systems etc. [28].
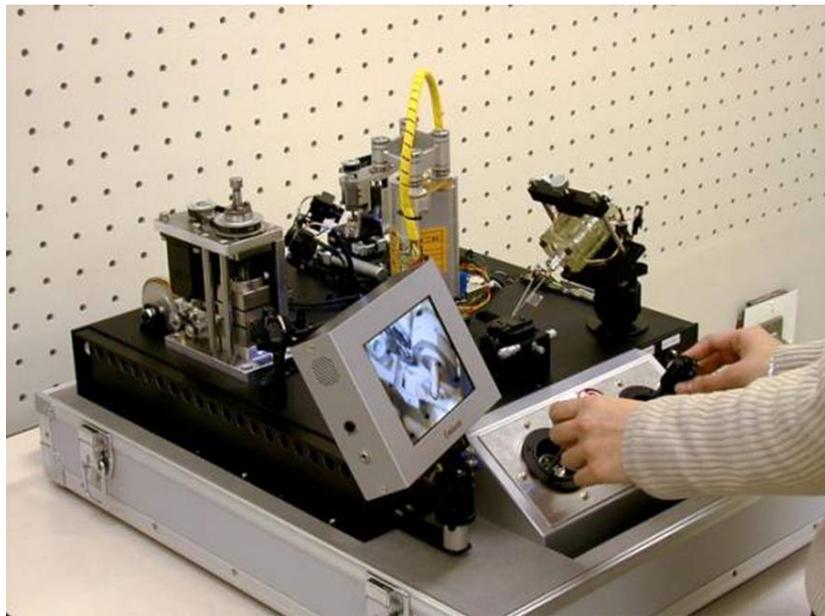

Figure 1:   A Micro Factory (Makoto et al, 2001)

1.10   **Micro Machines and Designs based on Flexures**

A 5-axis micro milling machine based on PC control system is presented in [29], the machine is designed from micro stages in market, control board that can be installed in PC and available air spindle. Stepping motors drive each stage therefore stages have high speed resolution. Another 5-axis micro milling machine based on PC control system is proposed in [30], the machine tool is supported throughout with aerostatic bearings and in addition these bearings are further assisted by squeeze oil-film. Diamond tool is proposed for cutting the job. There are shortcomings of these conventional technologies; high cost-effect, low natural frequencies, friction, low control and low accuracy, which can be overcome through use of

flexure-based compliant mechanisms. Different advantages can be accrue by using these mechanisms like cost effectiveness, frictionless joints, removal of backlash as in case of gears and compatibility to vacuum. A compliant mechanism can be described as a uniform shape structure whose working depends on its flexible material's deflection. It should be ensured that the compliant mechanism should work in elastic domain without inducing any plastic deformation by manipulating its structural parameters [31]. A 3-DOF compliant micro-positioning stage was presented in [32], which is developed using notch flexures. Three PZT actuators are used for actuation and are placed at 120 degrees apart in a symmetrical manner because of which large yaw motion can be achieved. A 2-DOF translational parallel micro-positioning stage was presented in [33]. The degrees of freedom for each stage are achieved by serially connecting different types of compound flexures. PZT actuation is used for micro/nano-positioning. The results showed good tracking and positioning performance. A simple idea of flexures to be used as control devices for linear stages was presented in [34] for the MEMS accelerometer design. A unique design where the flexures are used for controlling the rotation of rotary stage was presented in [35].

1.11   **Flexures**

Flexures are bearings that allow motion by bending load elements such as beams. In linkages the major error in motion can be produced by pin joints. These joints can be traded off with flexures when there is a requirement of only small motions. When these flexural linkages are used as joints in mechanisms they are referred to as compliant mechanisms. These can either be hourglass shaped hinges or long thin blades that can flex throughout their length. The later can have more deflection, but have a constraint that it is having more compliance in out-of-plane directions. Advantages using Flexures are [33]:

- Good Control.

- Motion devices having small range can be developed which are highly accurate.

- Ideal to be implemented in precision machines.

- Flexures are not affected by dirt.

Different types of flexure strips are in use generally categorized into parallel faces, cylindrical neck and elliptical neck. Ones with the parallel section i.e. rectangular shape amongst them are advantageous, they are generally easy to manufacture as these micrometer structures are used to be made by deposition of layers; though it is very difficult to make complex structures from the same process [36]. The motion of parallel face flexures is governed by lateral beam bending. The bending can be defined as a single dimensional element where the axis of the beam is perpendicular to the load applied. The load under consideration can be distributed all along or can be a concentration on a specific point; it can also be a combined situation. Euler–Bernouli beam equation states the basic formulae for the lateral beam bending. The displacement in flexures is related to the force acting at some point and the spring constant of the beam. A flexure's bending stiffness K when not subjected to tensile load can be represented as:

$$K = \frac{CEI}{L^3} \tag{1}$$

where I is moment of inertia,

$$I = \frac{wt^3}{12} \tag{2}$$

where,

w = Width of the flexible pivot

t = Thickness of the beam

E = Modulus of Elasticity

I = Moment of Inertia

L= Length of beam

C = Constant determined by the end to end configuration

The value of constant C can be depicted from the Figure 2 given below. With respect to end to end configuration the recommended values of C are shown against different configurations. For example the first figure shows a typical cantilever beam which is fixed at one end and the force is applied perpendicular to longitudinal axis at other end, the value of C to be taken as 3. The second figure shows the same beam however the load is uniformly distributed all over the beam, the value of C to be taken as 8. The third figure shows a pinned and a roller support at the ends and a point load at the center. The fourth figure shows pinned and roller supports at ends however the load is uniformly distributed all over the beam. The fifth and sixth figures show fixed supports at both ends with point load and distributed load respectively, the respective values of C are shown against each.
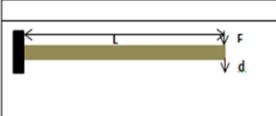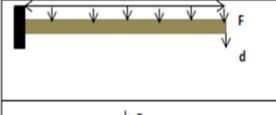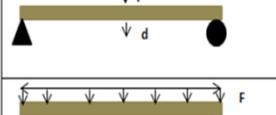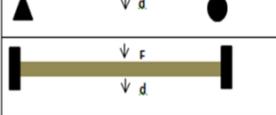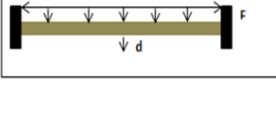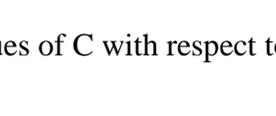

Figure 2:   Values of C with respect to Different Configurations

The Euler–Bernouli beam model is based on different assumptions which are:

- Isotropic material be used that should maintain homogeneity and follow Hooke's law.

- It is considered that beam's cross-section is constant and has initial straight orientation.

- Only pure bending is considered (i.e. no axial or torsional loads).

- Cross sections in y–z plane are considered to be unaffected during bending.

- Symmetry of axis is considered throughout the beam.

1.12   Micro Actuation

Applying force at micro-level is a special domain. Different types of actuating systems are available at micro-level that produce force on activation whereas research is under progress on mechanisms and actuators of this range. This particular area of research is termed as "micromechatronics", in the microscopic world it is the use of mechanics and electronics. Mostly the fabrication techniques used are IC manufacturing based compatible processes [37]. Commonly available systems are capacitance devices (transverse comb drive devices, lateral comb drive actuators), thermal actuators, electrostatic actuators and piezo actuators. Considering transverse comb actuators, the axis of action is orthogonal to the orientation of the fingers of the comb. The pros are that they are easy to fabricate and good for sensing the sensitivity of movement, however they are difficult to be used as actuators because of the physical limit of distance. When considering lateral comb actuators the force generated by them is proportional to the overlapped width and length of the fingers and inversely proportional to the separation among combs. They can be used where relatively long strokes are required from actuators. The output is mainly dependent on the thickness of fingers, the thicker they are the larger the force will be. However their foot print is relatively large. The working of thermal actuators is based on expansion of materials when subjected to heat; they can be solid, liquid or gas whereas

coefficient of thermal expansion (CTE) can characterize the expansion of solids. When considering working of lateral thermal actuators, they consist of two legs; one hot and thin other cold and wide; temperature difference is generated due to the different current flow densities in legs when heated by Joule heating. Joule/ohmic/resistive heating is a process when electric current is passed through a resistance and converted into heat. Due to the difference in temperature of legs the actuator deflects laterally, however the actuator can have only one axis of action which cannot be in reverse direction. The electrostatic actuators are fabricated usually with metals and dielectrics. They are precise in movement however they suffer from short range and pull in phenomenon. The piezo actuators are made up of piezo crystals. Piezo electric crystals are solid ceramic compounds that produce piezo electric effects i.e. when mechanical force is applied on piezo crystals electric voltage is produced or when electric voltage is given to crystals the mechanical deformation is induced. Natural piezo electric crystals are quarts, tourmaline and sodium potassium tartrate. A servo-controller can be used to determine the input voltage given to the PZT ceramics that compares the signal from actual position sensor with a reference signal, which in turn will control the movement of the actuator. The main advantages of piezo actuators are their accuracy and repeatability whereas they are very stable and have linearity. The piezo actuators have unlimited lifetime i.e. no wear and tear; it is proved that they can perform billions of cycles without any measurable wear. They have virtually infinite stiffness (within load limits) and there will be very little hysteresis and creep effects [36].

2　A Smart Micro Factory Approach

2.1　Scenario Details

A micro factory approach is visualized which is operating in a socially safe environment whose operations are handled through a cyber-physical system. The micro factory contains high

precision micro/nano positioning stage installed on a tabletop sized machine tool. A flexure based, 3-axis micro positioning stage is considered that can be installed on a desktop size milling machine. A collaborative robot is envisaged to perform operations, handle micro parts in the presence of human operator who is on a supervisory role. The micro-size and delicate nature of the parts demand sensitive collision prevention, precise controlled operations and safe handling. The smart micro factory is designed in two portions; initially a micro stage is proposed for handling milling operations at micro level that will be placed on a table top machine tool, secondly a collaborative robot is proposed for safe handling of micro parts. For safety handling a new technique is suggested based on virtual domain. A new concept of psychological safety of system is introduced while handling collaborative operations in the presence of a human supervisor.
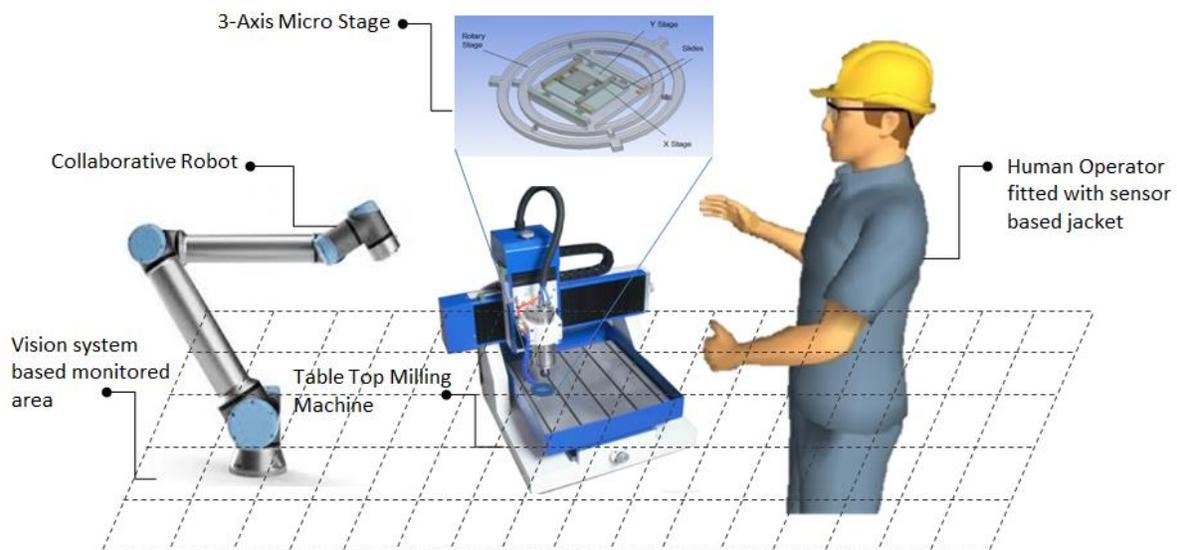
Figure 3: Proposed Micro Factory Scenario

2.2   **Development on the Physical Domain**

2.2.1   **Design of the Proposed Micro Stage Design**

A micro-stage is designed in SolidWorks software. Three stages were made overlapping each other. The prototype is specifically designed to achieve small range of motion through these stages i.e. in micrometers that can be used in a machine tool for micro fabrication. Piezo actuators are used in each stage to produce lateral motion that will be converted into linear and rotary motion as per the design of each stage. The idea of linear stages was adopted from the MEMS accelerometer design in [34]. The idea of rotary stage was adopted from the design in which flexures are used for rotation [35]. Figure shows the design of 3 axis micro stage in which the stages are clamped through bridges (flexures) connected with subsequent stages. When the force is applied through piezo devices the flexures are bent and motion is produced as per the stage design. The range of motion depends upon the stress limits of flexures that will be produced due to induced motion. The flexures used in the design can be considered as fixed-free beam configuration.
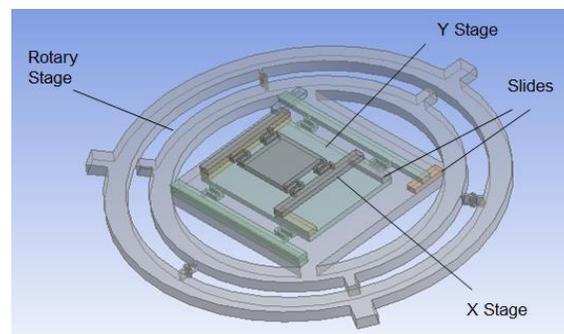

Figure 4: Design of Micro Stage without Piezo Actuators
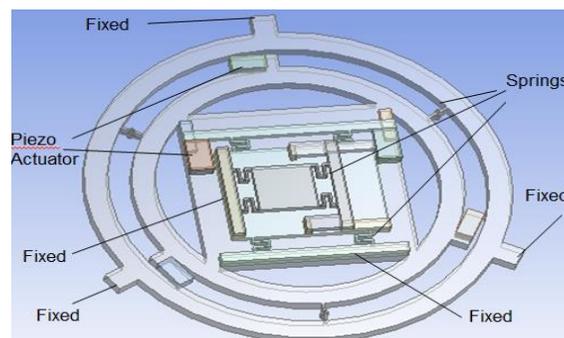
Figure 5: Design of Micro Stage with Piezo Actuators and Boundary Conditions

Actuation mechanism is shown in Figure 6 where piezo actuators are used for producing controlled range of motion.
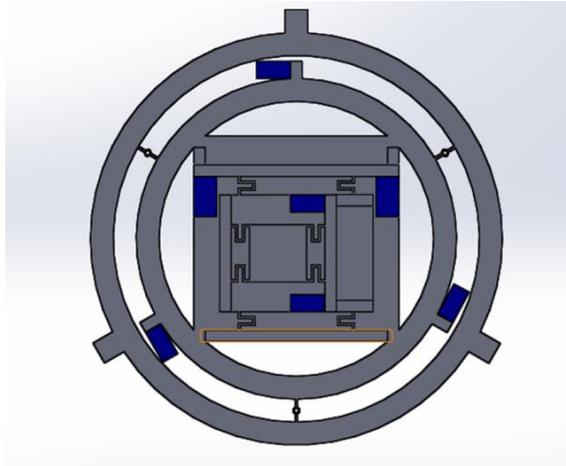

Figure 6:   Piezo Actuators shown in Blue

Following design specifications were used for the prototype structure as shown in Figure 7.
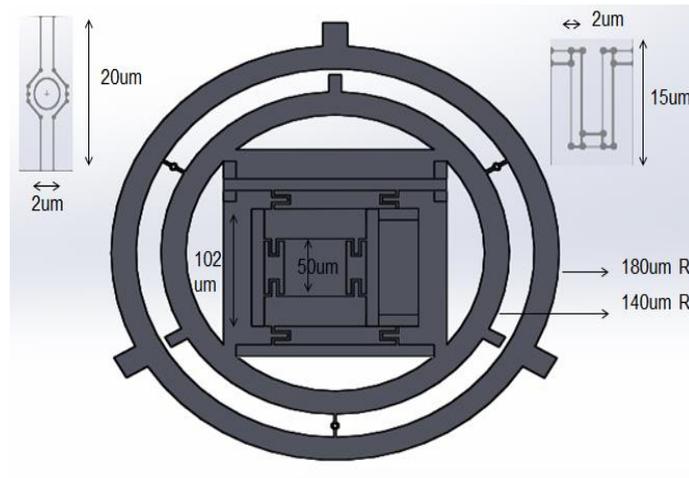
Figure 7: Specifications of Prototype in µm

The other specifications related to thickness are:

- Thickness 1st stage   -   6 µm

- Thickness 2nd stage   -   6 µm

- Thickness rotary stage   -   12 µm

- Thickness for inner springs   -   6 µm

- Thickness for outer springs   -   6 µm

2.2.2 Material Properties

Three commonly used materials for micro machining were considered and later were analysed for stress and deflection properties. A table showing material properties is given:

TABLE I
MATERIAL PROPERTIES

	Silicon	Gold	Steel
Density (kg/m^3)	2330	19320	7850
Young modulus (GPa)	165	98.5	200
Poisson ratio	0.22	0.42	0.3

2.2.3 Methodology

- Design Dimensions were selected for micro scale.

- The prototype was designed in SolidWorks and the file then imported in ANSYS.

- Modal Analysis of the structure was carried out.

- Prototype's structural analysis for maximum deflection was then performed in ANSYS.

- Material properties were given for three different materials i.e. silicon, steel and gold.

2.2.4 Mathematical Formulation

Following mathematical formulas were considered for the particular design; however the precise results can be calculated from FEM analysis:

Moment of Inertia (I)

Moment of inertia (I) of the flexural beam used in the design can be calculated through:

$$I = \frac{wt^3}{12} \tag{3}$$

Stiffness of springs (k)

Stiffness of single beam (k) as estimated from (2):

$$k = \frac{3EI}{L^3}$$

(4)

Stiffness of X Stage

- $K = 8 \times 3\ EI/L^3$

(5)
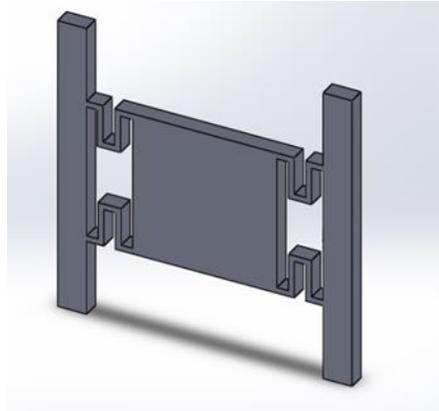
Figure 8:   X stage

For the 8 springs in X stage; w was taken 6 µm, L was taken 15 µm and t was taken 2 µm.

*Stiffness of Y Stage*

- $K = 8 \times 3\ EI/L^3$

(6)
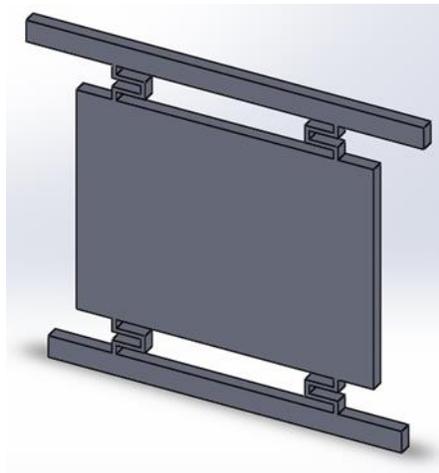
Figure 9:   Y Stage

For the 8 springs in Y stage; w was taken 6 µm, L was taken 15 µm and t was taken 2 µm.

Stiffness, Total Force and Rotation of Rotary Stage

- $K = 3 \times 3 \, EI / L^3$ (7)

- $3F = 3 \times K \, d$ (8)

- $tan \, theta = d / R$ (9)

where theta is the rotation, d is the deflection and R is the radius of the stage.
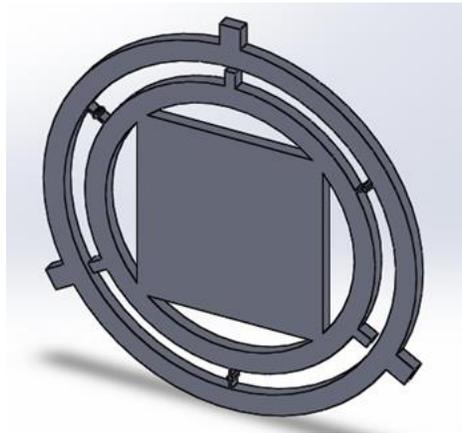
Figure 10:   Rotary Stage

For the 3 springs of rotary stage; w was taken 12 µm, L was taken 20 µm and t was taken 2 µm.

2.2.5 Meshing

Meshing of the structure in ANSYS is shown:
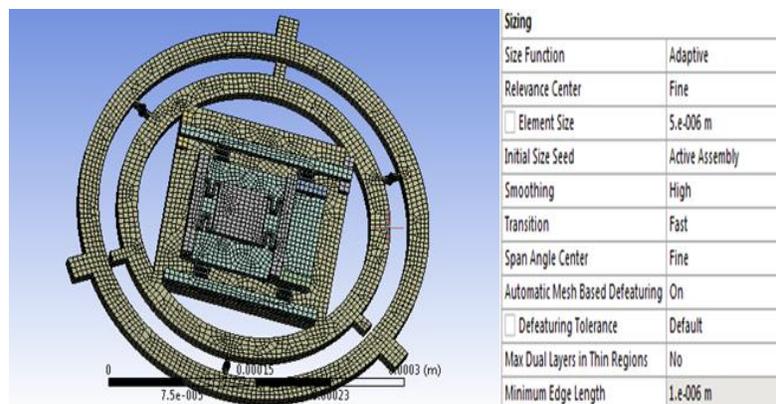
Figure 11:   Meshing of Structure

2.2.6   **FEM Analysis**

Modal analysis followed by structural analysis of the prototype was performed in ANSYS. Details are covered as under:

2.2.6.1 **Modal Analysis**

Initial six modes were calculated from modal analysis for the designed prototype as shown in Figure 12. The 4th mode conforms to the desired motion.
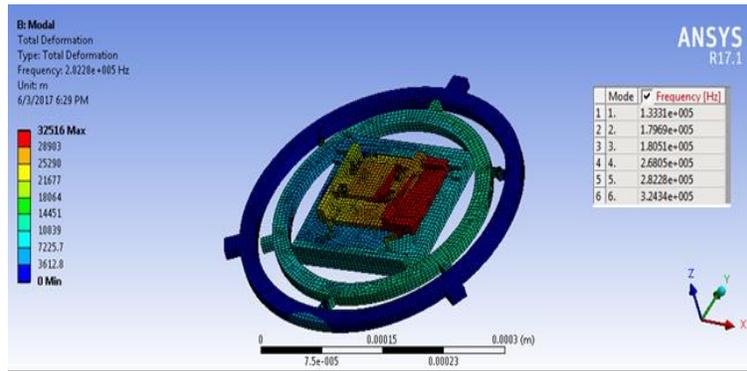
Figure 12:   Modal Analysis

Different modes, their frequencies and mode shapes are given in tabulated form:

TABLE II

FIRST 6 FREQUENCY MODES OF PROTOTYPE

Ser	Mode	Frequency (Hz)	Mode Shape
1.	1	1.3331e+005	
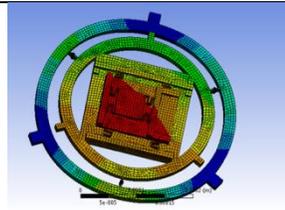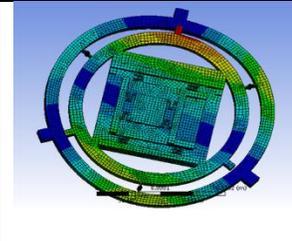
2.	2	1.7969e+005	
3.	3	1.8051e+005	
4.	4	2.6805e+005	
5.	5	2.8228e+005	
6.	6	3.2434e+005	
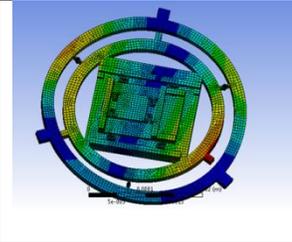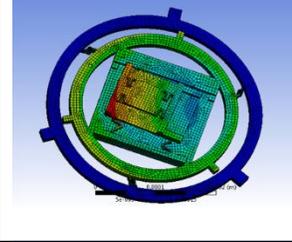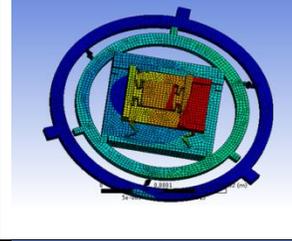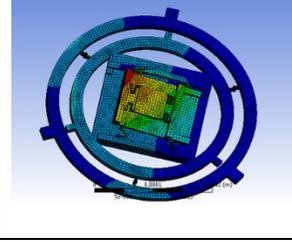
2.2.6.2 **Structural Analysis**

Structural Analaysis for X, Y and rotary stage were carried out. A force ranging from 100μN to 1N was applied through each piezo actuator to get the finest resolution of each stage while using particular material. The maximum stress in the structure was obtained at each force level to ascertain the working of structure below yield stress. Maximum deformations for each

stage using all materials were calculated and compared to find the best material for the best design.
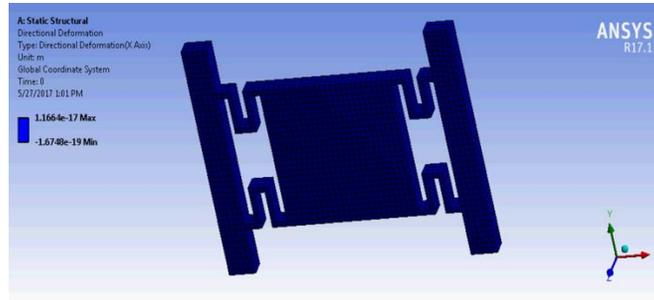
Figure 13:   X Stage Static Structural Analysis (Deformation of X stage)
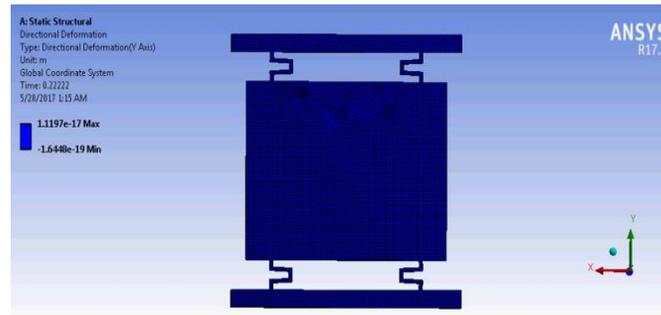
Figure 14:   Y Stage Static Structural Analysis (Deformation of Y stage)
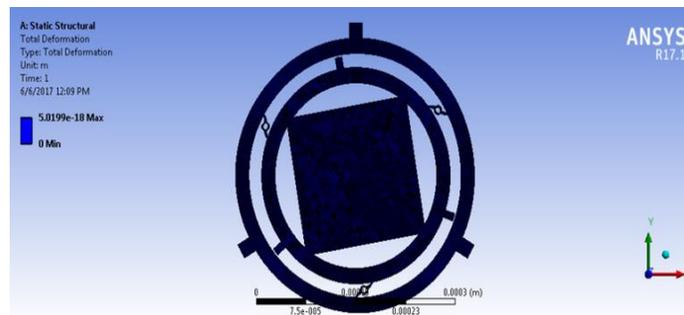
Figure 15:   Rotary Stage Static Structural Analysis (Deformation of Rotary stage)

2.2.6.7 **Results**

The results show that 100μN force on single actuator is the safe limit for this particular design as the obtained stress is quite below the yield stress in spite using any material; however

the maximum deflection can be obtained when gold is used for the structure. The material which shows minimum 'stress to yield stress ratio' when the same structure made from it of similar specifications subjected to same load is found to be steel.

TABLE III
RESULT OBTAINED FROM THREE STAGES DESIGNED WITH DIFFERENT MATERIALS SUBJECTED TO DIFFERENT LOADS

Stage	Material	Force	Yield Strength	Obtained Stress	Deflection(m)
X stage	Gold	1N	205 MPa	1203.9 GPa	2.2709e-003
		100μN		120.39 MPa	22.709 e-6
Y stage		1N		1168.3 GPa	2.1724e-003
		100μN		116.83 MPa	21.72 e-6
Rotary stage		1N x 3		1049.2 GPa	95.283e-003
		100μN x 3		104.92 MPa	952.83 e-6
X stage	Steel	1N	250 MPa	1123.3 GPa	1.1679e-003
		100μN		112.33 MPa	11.67 e-6
Y stage		1N		1091.1 GPa	1.12e-003
		100μN		109.11 MPa	11.2e-006
Rotary stage		1N x 3		1030.6 GPa	50.199e-003
		100μN x 3		103.06 MPa	501.99 e-6
X stage	Silicon	1N	180 MPa	1092.2 GPa	1.4423e-003
		100μN		109.22 MPa	14.42e-6
Y stage		1N		1061.3 GPa	1.3844e-003
		100μN		106.13 MPa	13.84e-6
Rotary stage		1N x 3		1038.2 GPa	62.6 e-003
		100μN x 3		103.8 MPa	626 e-6

The comparison for the maximum deflection obtained when three different materials are used for each stage is shown in Figure 16:
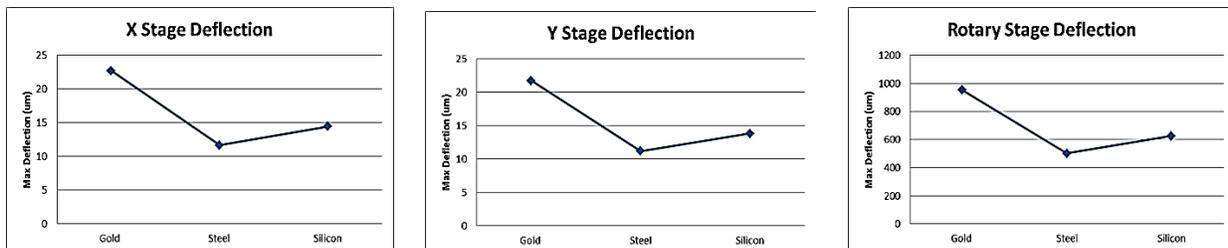

Figure 16:   Comparison of Maximum Deflection of Different Stages when 100μN Force given to Each Actuator

The comparison for the stress obtained when three different materials are used for each stage is shown in Figure 17:
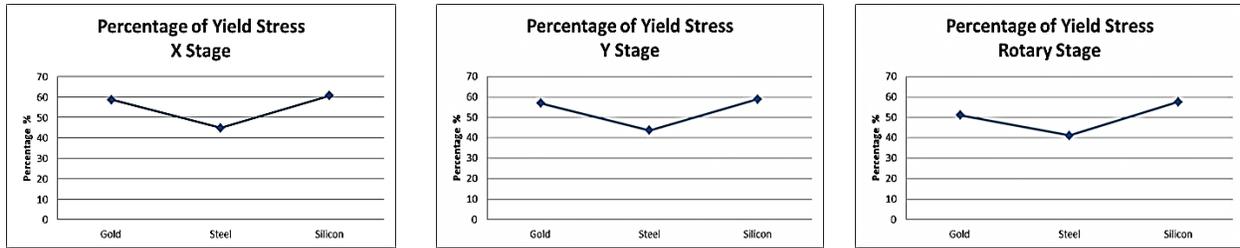
Figure 17:   Comparison of Percentage of Maximum Stress to Yield Stress for All Stages

2.3   Development on Virtual Domain

2.3.1   Social Safety of Cyber-Physical System

With increasing human and machine interaction, latest cyber-physical systems are designed to cater for aspects of social space [38]. Information is transferred among their computational, physical and social elements through multiple modes that may be verbal, physical gestures or social gaze. The cognitive status and the physical state of the human operator need to be ascertained real-time. This means that human intention will be inferred by the CPS by measuring his activity (recognise, understand and participate in communication situations), these intentions will then be analysed and converted into possible tasks to be performed in the physical domain. A common workspace is shared by the human and the robot, so the expectation is that they acquire common goal through interaction while obeying the rules of social norms. Here comes the part of cobots; while performing joint actions and obeying rules of social domain like proxemics they must act in an efficient and legible way [39]. The basis of intelligent and social robots is taken from social intelligence in humans and other social animals. The qualities of robot in this domain depend on particular application for which it is used; for example a robot delivering the mail in an office environment will have regular encounters with customers and

will be requiring well-defined social skills. Whereas a robot that has to assist old or disabled people must be in possession of a wide range of qualities and social abilities to make it convenient for humans [40]. Prospects of the social robots in the food industry was presented in [41] that elaborates the roles of robots from food industry to serving robots, keeping in view the social norms like cleanliness to social interaction with humans. The concept has extended to real-time safety system capable of allowing safe human-robot interaction. Safety can be classified into two categories physical safety and psychological safety [42]. The first one is only related to unwanted human robot contact whereas the second one is related to human robot interaction that does not cause stress and discomfort for long periods. A conceptual system avoiding both contact and stress is presented in [43]. A real time safety system was formulated that works at very low separation distance; the system does not require any replacement or modification in robot hardware. The real time measurement of separation distance thus found can be used for precise robot speed adjustment. A 3D sensor is used in the system which formulates a dynamic safety zone and calculates the safety distance. Collision can be prevented between humans and robot thus making it comfortable for human operators to work stress free and for robots to do their work efficiently; this can be done by leveraging known robot joint angle values and accurate measurements of human positioning in the workspace. A matching idea for human psychological comfort due to the effect of robot motion is presented in [44]. A safe human robot collaboration (HRC) is proposed in [45] for heavy payload industrial robots, an integrated concept is used by combining the concept of security and safety using off the shelf sensors and components of cyber physical system. A defensive strategy to avoid cyber physical attacks is proposed for safety of cyber physical systems in [46], the concept includes secured data monitoring at different nodes based on the technique of system reconfiguration and health monitoring. Three categories of

robot motion were compared, based on the criteria of human comfort when exposed to particular type of motion. The categories presented were functional, predicable and legible motions. Overall, the work supports the use of legible motion over predictable in collaborative tasks; both are types of functional motion. Functional motion is the one in which the robot reaches the goal without collision, though not efficient, predictable motion is one that matches collaborator expectation given the goal is known whereas in legible motion the human infers the goal while the robot is undergoing motion. While the comfort for human operator increased the system lacks flexibility to encounter any contingency in task, for example in a manufacturing line the robot while performing work on a nut found a bolt. Different human robot interaction safety systems are presented in [47], [48], [49], [50]. Mainly two types of sensors are used in broader category, one based on vision systems and the other based on proximity/contact. The safety system presented will come into action as soon as the human arm will come into contact or in near vicinity to the robot, however these systems do not provide the choice to identify the user. Also they do not take into account any foreign element just for example a pet if enters into the work zone. A list of the state of the art existing collaborative robots is presented in [51] showing their capabilities for safe human and robot collaboration. The list shows that force sensors, torque sensors and visual/IR cameras are used for collision detection. The review identifies that the robots lack particular object/user detection in its workspace during operation. An object classification technique was however used in [52] to identify a human body and some objects available in workspace. The objective is to classify objects in areas of interest of the robot, real-time. However the system neither cannot differentiate between other humans than the user nor can detect other objects which are not related to task and nor can modify the role if an object currently not defined for this particular task. As the industry 4.0 recommend the use of intelligent

robots, the concept of comfort to human users can be equally valid for intelligent robots i.e. physical and psychological safety both. As already discussed a lot of work has been done for physical safety of both humans and robots but there is no concept of psychological safety for intelligent robots/systems. Safety cannot be termed in the sense of avoiding collision only rather avoidance/modification of task when the robot/system is not comfortable. Changing scenarios diverting from the main task affects the efficiency of system which must be catered keeping in view the optimization criteria not compromising the safety. Affecting efficiency means uncomfortable situation for the system or eventually the intelligent robot. This may be in terms of entrance of unwanted object in the workspace or a changing scenario, may be in terms of wrong feed of parts in manufacturing system. The problem can be addressed using detection of particular type of object within the work zone and then taking action through predefined logic.

2.3.2 **Methodology**

- A micro-factory based on table top size machine tool is proposed.

- The machine tool will be fitted with 3-axis micro positioning stage for milling operations.

- A collaborative robot (UR 3) fitted with microgripper will be placed next to micro factory for handling micro parts.

- A human operator will be present for supervision and control of complete operation with in the work space.

- The cobot will take input from laptop fitted with a machine vision camera.

- An object detection based algorithm will be used to detect objects with in the workspace and give inputs to cobot for safety and control operations.

- Hazard assessment based on predefined logic may be used to provide social psychological safety to the system.

2.3.3 UR3 Robot Components and Capability

The UR3 is a small table-top collaborative robot; it can be used for automated workbench tasks of light payload scenarios. It is a compact table-top robot which can handle payload of 6.6 lbs (3 kg), but its weight is only 24.3 lbs (11 kg), it has a capability of infinite rotation on the end joint and 360-degree rotation on all wrist joints. The robot system consist of three main parts the robotic arm, the teach pendent and the controller box. The controller box contains both digital and analog input and output sockets which can be used for interfacing other components or system components itself. The teach pendant can be used to program the robot as per the requirement of user, can be based on inputs and outputs. The robot can be set up quickly without programming experience using patent technology and can be operated with 3D intuitive visualization. It requires a simple movement of the robotic arm by giving waypoints or from the controls given on the touch pad. UR Robots can be set-up very quickly; thus can reduce usual deployment that can take weeks and can be done in hours. The average time calculated is half day. It can only take an hour to unpack, by an un-experienced operator and even to program it first time with a simple task. They are lightweight, can save space, easy to install/relocate and can be used for multiple applications without changing layout of factory. Altering UR3 to new processes is quick and easy, giving the agility to automate almost any manual task, they can even handle small batches or quick change-overs. The programs can be reused for recurrent tasks. No safe guards are required when using UR robot, almost eighty percent of the thousands all over the world perform with no safety guarding, along with humans. It is approved and certified by TÜV (The German Technical Inspection Association).

2.3.4 **Object Detection API**

The Object Detection API is one of the frame works provided on an open source of TensorFlow or YOLO algorithm. These provide an opportunity to construct models very easily and then train and deploy different models. They had broken the challenge faced by machine vision developers for creating a model which can accurately localize and identify multiple objects in a single image. A tutorial on the object detection is placed in Appendix at the end of this chapter. The images for the sample test are shown in Figure 18 and Figure 19 below:

Figure 18:   First Image for Test

Figure 19:   Second Image for Test

The results after the program was run on the test images are shown in Figure 20 and Figure 21 below. The algorithm correctly identified the objects in the pictures. Same can be run for real time video after little modification in the algorithm.

Figure 20: Result of Object Detection API on First Image
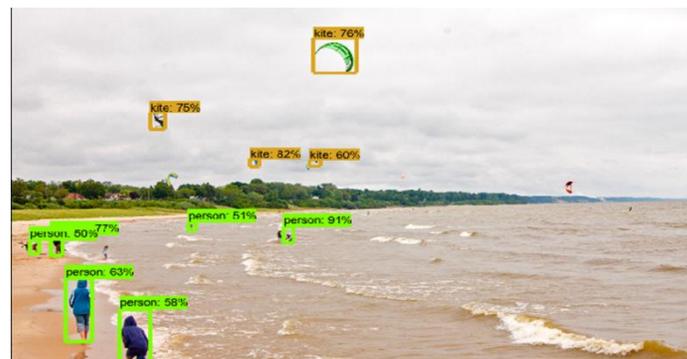
Figure 21: Result of Object Detection API on Second Image

2.3.5 Hazard Assessment

Level of interaction and risk play major role in defining effective human robot collaboration. A formal grading to ascertain human robot collaboration is introduced in [51], a concept of risk and hazard assessment was introduced in [45], [53] along with HRC assessment. Based on the similar approach number of hazards are outlined on different criteria i.e. hazard posed by Robot, industrial process and Robot control system. These hazards are then gauged against social space characteristics and graded a particular value. An effective collaborative

system can be designed based on the assessment carried out through this process. For this a chart considering all possible scenarios is developed which will be helpful for risk/hazard assessment. The particular type of hazard will identify that which output is affected to which level. This on the other hand can be used as a predefined logic for an automated system by using AI algorithms and will be helpful in providing social psychological safety to the system. This also can be used as a checklist to design a working cell for human robot collaboration. Possible hazards for different categories are stated below in a table format where a number is assigned to each; the number can be identified by combining the category number and the hazard number.

TABLE IV

HAZARD POSED TO CYBER PHYSICAL PRODUCTION SYSTEM FROM ROBOT, INDUSTRIAL PROCESS AND CONTROL SYSTEM

(a) Hazards from robot during collaboration
1. Robot characteristics: speed, force, torque, acceleration, momentum, power etc.   2. Operator dangerous location of working under heavy payload robot.   3. Hazards from end-effector and work part protrusions.   4. Sensitivity of the parts of the operator body that can come in contact in case of collision.   5. Mental stress to operator due to robot characteristics (e,g., speed, inertia etc.)   6. Hazard from trajectory taken by the robot.   7. Physical obstacles against robot operation during collaboration.   8. Hazard from fast worker approach speed and robot's slow reaction time.   9. Hazard from tight safety distance limit in the collaborative workspace.   10. All parts of the robot are not covered using the safety distance approach.
(b) Hazards from the industrial process during collaboration
1. Ergonomic design deficiency.   2. Time duration of collaboration in the process.   3. Transition time from collaborative operation to other operation.

4. Potential hazards from the industrial process (e.g., temperature, loose parts etc.).
5. Mental stress to operator due to collaborative industrial process.
6. Work material routing during the process.
7. Physical obstacles tackled by worker in order to accomplish process requirement in collaborative workspace.
8. Hazards due to task complexity in collaborative workspace.

(c) Hazards from robot's control system malfunction during collaboration

1. Hazards from biomechanical pressure limits for operator during reasonably foreseeable misuse.
2. Misuse of collaborative system by operator or under a cyber-attack in a connected environment.
3. Physical obstacles in front of active sensors used in the collaborative workspace. (e.g. obstacle in front of camera).
4. Non-provision of transition from collaborative operation to manual system in case of system malfunction.
5. Number of workers involved in the collaborative process.
6. Hazard created due to wrong perception of industrial process completion by the robot.
7. Hazards from obstacles against unobstructed means of exiting the collaborative workspace at any instant.
8. Hazard from visual obstruction for robot in collaborative workspace due to vantage point of operator.

The grading criterion for hazard assessment is stated as under:

- High influence on output: 3

- Medium influence on output: 2

- Low influence on output: 1

- No influence on output: 0

A score chart based on the grading criterion by pitching hazard against social space characteristics is given as under:

TABLE V

HAZARD ASSESSMENT SCORE CHART

		Hazards	Social Space Characteristics				
			Industrial process quality	Quality of HRC	Collaborative system security	Operator safety	Operator health
Hazards	Robot	1a	0	3	0	3	3
		2a	0	3	0	2	2
		3a	0	3	0	3	2
		4a	0	2	0	3	2
		5a	0	3	1	2	3
		6a	1	1	0	1	1
		7a	1	2	0	2	1
		8a	0	3	0	3	2
		9a	0	3	0	3	2
		10a	0	3	0	3	2
	Industrial Process	1b	2	2	0	2	2
		2b	0	2	0	2	1
		3b	1	1	0	1	0
		4b	3	3	1	3	3
		5b	2	2	1	2	3
		6b	2	2	0	2	0
		7b	2	2	0	2	0
		8b	1	2	0	2	1
	Robot Control System Malfunction	1c	1	2	0	3	2
		2c	3	3	3	2	0
		3c	3	3	1	3	0
		4c	2	2	1	2	1
		5c	1	1	2	1	0
		6c	2	1	0	2	0
		7c	0	1	0	3	1
		8c	2	2	0	2	0

3 Conclusion

Recent developments in research related to smart factory have paved the way for development of new scenarios. Two different approaches in physical and virtual domains are dovetailed and presented in a scenario of micro factory i.e. a cyber-physical production system is envisaged incorporating both domains to ensure improvement in product quality, process improvements, physical and social safety, mass customization and mass production. First a 3-axis micro stage was presented based on flexure design. The results showed that use of piezo-actuators ensured deflection of micro-machine stages in micro-meter range. Secondly a virtual

domain was considered based on vision system in collaboration with a collaborative robot which ensured satisfactory performance of task keeping in consideration the social safety constraints. A new concept of psychological safety of the system was introduced that will provide comfort to the system ensuring optimum utilization. The simultaneous approach that incorporated both the domains collaborated in real time for a smart micro factory has opened a new avenue of research for the particular domain.

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5   Appendix: Tutorial on Object Detection API

Object Detection API in the TensorFlow requires following libraries:

- Tensorflow

- Python-tk

- Pillow 1.0

- Protobuf 3+

- lxml

- tf Slim

- Matplotlib

- Jupyter notebook

- Cython

- Cocoapi

Tensorflow can be installed by using one of the following commands:

```
# For CPU
pip install tensorflow
# For GPU
pip install tensorflow-gpu
```

The remaining libraries can be installed on Ubuntu 16.04 using via apt-get:

```
sudo apt-get install protobuf-compiler python-pil python-lxml python-tk
sudo pip install Cython
sudo pip install jupyter
sudo pip install matplotlib
```

Alternatively, users can install dependencies using pip:

```
sudo pip install Cython
sudo pip install pillow
sudo pip install lxml
sudo pip install jupyter
sudo pip install matplotlib
```

The Anaconda is another open source which makes it even easier to cater for machine learning and Python data science. There are more than 250 famous data science packages, virtual environment manager for Windows, conda packages, MacOS and Linux packages. TensorFlow, Scikit-learn and SciPy are easy to be installed in Anaconda; it is even easy to upgrade environments and complex data packages. Anaconda 3 includes all the libraries required for object detection API. The Tensorflow Object Detection API uses Protobufs to configure model and training parameters. Before the framework can be used, the Protobuf libraries must be compiled. Protobuf 3.4 is required for compilation, others don't work. Either add protbuf in

system path or give full path to the protos folder. This should be done by running the following command from the tensorflow/models/research/ directory:

```
# From tensorflow/models/research/
protoc object_detection/protos/*.proto --python_out=.
```

Anaconda 3 which is a python environment is used for running all the libraries. After downloading all the libraries and compiling the protos folder in object detection module, open jupyter notebook in anaconda prompt. In the prompt give the path where object detection folder is present like:

E:\Software\tensorflow\model\models-master\research.

Inside it find the file object detection tutorial.ipynb and convert it to .py file. After running jupyter notebook, it may happen that internet explorer will open but nothing will happen. A token will appear on screen on command prompt. Copy that token in word and place this token in google chrome, jupter notebook will open where file format is to be converted. Then open another anconda prompt and run spyder in it. In spyder open the object-detection.py file and run the cells of the program one by one. Detail description of cells and their purpose is given below:

The cell which imports all the libraries is shown in Figure 22:

```python
import numpy as np
import os
import six.moves.urllib as urllib
import sys
import tarfile
import tensorflow as tf
import zipfile

from collections import defaultdict
from io import StringIO
from matplotlib import pyplot as plt
from PIL import Image

# This is needed since the notebook is stored in the object_detection folde
sys.path.append("..")
from object_detection.utils import ops as utils_ops

if tf.__version__ < '1.4.0':
  raise ImportError('Please upgrade your tensorflow installation to v1.4.*

# ## Env setup
```

Figure 22:   Part of Program that import Libraries

The cell shown in Figure 23 imports mataplotlib for images:

```
# This is needed to display the images.
get_ipython().run_line_magic('matplotlib', 'inline')
```

Figure 23:   Part of Program that imports mataplotlib

The cell shown in Figure 24 provides the path and name of the model that is required for object

detection:

```
# In[ ]:


# What model to download.
MODEL_NAME = 'ssd_mobilenet_v1_coco_2017_11_17'
MODEL_FILE = MODEL_NAME + '.tar.gz'
DOWNLOAD_BASE = 'http://download.tensorflow.org/models/object_detection/'

# Path to frozen detection graph. This is the actual model that is used for
PATH_TO_CKPT = MODEL_NAME + '/frozen_inference_graph.pb'

# List of the strings that is used to add correct label for each box.
PATH_TO_LABELS = os.path.join('data', 'mscoco_label_map.pbtxt')

NUM_CLASSES = 90
```

Figure 24:   Part of Program that downloads Object Detection Model

The cell below extracts the model and is not required to run if model file is already downloaded

and extracted:

```
# In[ ]:



opener = urllib.request.URLopener()
opener.retrieve(DOWNLOAD_BASE + MODEL_FILE, MODEL_FILE)
tar_file = tarfile.open(MODEL_FILE)
for file in tar_file.getmembers():
  file_name = os.path.basename(file.name)
  if 'frozen_inference_graph.pb' in file_name:
    tar_file.extract(file, os.getcwd())


# ## Load a (frozen) Tensorflow model into memory.
```

Figure 25:   Part of Program that extracts the Downloaded Model

The cell shown in Figure 26 loads the model:

```
# In[ ]:


detection_graph = tf.Graph()
with detection_graph.as_default():
  od_graph_def = tf.GraphDef()
  with tf.gfile.GFile(PATH_TO_CKPT, 'rb') as fid:
    serialized_graph = fid.read()
    od_graph_def.ParseFromString(serialized_graph)
    tf.import_graph_def(od_graph_def, name='')
```

Figure 26:   Part of Program that loads the Model

This cell in the Figure 27 loads the labels:

```
# In[ ]:


label_map = label_map_util.load_labelmap(PATH_TO_LABELS)
categories = label_map_util.convert_label_map_to_categories(label
category_index = label_map_util.create_category_index(categories)


# ## Helper code
```

Figure 27:   Part of Program that loads the Labels

The cell shown in Figure 28 converts the image into array:

```
# In[ ]:


def load_image_into_numpy_array(image):
  (im_width, im_height) = image.size
  return np.array(image.getdata()).reshape(
      (im_height, im_width, 3)).astype(np.uint8)


# # Detection
```

Figure 28:   Part of Program that converts Images into Array

This cell shown in Figure 29 gives path to the images and declares the image size:

```
# In[ ]:


# For the sake of simplicity we will use only 2 images:
# image1.jpg
# image2.jpg
# If you want to test the code with your images, just add path to
PATH_TO_TEST_IMAGES_DIR = 'test_images'
TEST_IMAGE_PATHS = [ os.path.join(PATH_TO_TEST_IMAGES_DIR, 'image

# Size, in inches, of the output images.
IMAGE_SIZE = (12, 8)
```

Figure 29:　　Part of Program that provides Image Path and Size

The cell shown in the Figure 30 contains the main model, it takes in input images in a loop and

converts them into an array, identify classes, show result in form of boxes, classes and score:

```
# In[ ]:


for image_path in TEST_IMAGE_PATHS:
  image = Image.open(image_path)
  # the array based representation of the image will be used late
  # result image with boxes and labels on it.
  image_np = load_image_into_numpy_array(image)
  # Expand dimensions since the model expects images to have shap
  image_np_expanded = np.expand_dims(image_np, axis=0)
  # Actual detection.
  output_dict = run_inference_for_single_image(image_np, detectio
  # Visualization of the results of a detection.
  vis_util.visualize_boxes_and_labels_on_image_array(
      image_np,
      output_dict['detection_boxes'],
      output_dict['detection_classes'],
      output_dict['detection_scores'],
      category_index,
      instance_masks=output_dict.get('detection_masks'),
      use_normalized_coordinates=True,
      line_thickness=8)
  plt.figure(figsize=IMAGE_SIZE)
  plt.imshow(image_np)
```

Figure 30:　　Part of Program that contains the Main Model

Place the images in the image path folder and run the program to get results.