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ROBOT AUTONOMY SPECTRUM FOR PROPER ADOPTION OF ROBOTS IN CONSTRUCTION INDUSTRY

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ABSTRACT

Adoption of Fully autonomous robot in the Construction industry is not feasible, directly as it requires complex integration with technology. Hence, in this paper a Robot Autonomy Spectrum is developed so that the construction industry can adopt the robot properly from existing construction machinery. Robot Autonomy Spectrum has on one extreme side construction machinery whereas fully autonomous robots on the other side. The paper also shows that how the role of humans and robots will change during Robot Autonomy Spectrum.

Key words: Robot Autonomy, Construction industry, Robot autonomy Spectrum

Introduction:

The Construction industry, is fast developing throughout the world. However the construction industry is labor intensive, fragmented, technological stagnant, low R&D, unsafe working practices; hence, robots adoption can help construction (Jain, and Phadtare, 2013). By adopting robots in the construction industry, there will be an increase in productivity, quality, safety, competitiveness and reduction in construction time, labor, and the cost of construction (Jain, and Phadtare, 2013; Rajgor, and Pitroda, 2013). Also automation and robotics implementation in construction has large scope, including all stages of the construction life cycle (Struková, and Líška, 2013).

(Mohr et. al., 2009) observed that modularity can be used for building a complex product, which can be built up from smaller subsystems. These subsystems can be designed independently to function together as a whole. Modularity reduces uncertainty in product design and results in product standardization; and it is better, more incremental rather than breakthrough innovation. (Mohr et. al., 2009) defined product platform as a common architecture based on a single design and underlying technology. The New product platform enhanced performance benefits and called as next generation products. Platform and derivative strategy were useful in high technology product (like robots) as the production cost of the first unit was very high; however developing derivative product has a smaller incremental cost. When a firm wanted to introduce a breakthrough product it would create gaps in the marketplace. Adopter firm had to migrate through these gaps, and if developer firms do not look in these gaps competitors will allow new strategies to fill them. Hence a new product can be introduced in stages (Mohr et. al., 2009); since fully autonomous robot is also a high technology product which must be introduced in stages, also autonomy in robot plays an important role, hence in this paper incremental improvement in robot autonomy is considered as a spectrum called as Robot Autonomy Spectrum.

Following sections consider the development of Robot Autonomy Spectrum, its detail and change of the role of human and robot.

1. **Development of Robot Autonomy Spectrum**:

Autonomy in context of robot is the extent to which Robot can Sense, Plan, and Act upon the environment, with the intent of reaching a goal which is given or created by robots, with little or no external control (Jenay et. al., 2012).

Autonomy is context of a system, i.e. robot is the capability for the system to operate independently from external control and as per NASA spectrum, it may be from basic automation (mechanistic execution of action or response to stimuli) to fully autonomous systems (able to act independently in a dynamic and uncertain environment).

Many researchers also observe that level of autonomy in robot is a continuum and robot autonomy has many levels i.e. 10 levels (Jenay et. al., 2012; Jenay et. al., 2014); 12 levels

(Riley, 1989). However, these levels can be reduced to four levels. These four levels include: Remote control; Tele-operation; Semi-autonomous; and Fully-autonomous (Clothier et. al., 2013).

Autonomy has two application areas i.e. increased use of autonomy to enable an independent acting system; automation as an augmentation of human operation (Rob et. al., 2010). Similarly

(Jenay et. al., 2014) also considered that autonomy in case of human robot interaction (HRI) can be in two levels, i.e. higher robot autonomy requires less frequent HRI; and higher robot autonomy needs higher levels of HRI. In the following section, these two thoughts are considered.

1.1 **Higher robot autonomy needs high levels of HRI**:

(Kai et. al., 2008) observed that implementation of a human robot system where a robot is not directly controlled by humans can be very challenging; also the interaction mode depending on task context can be continuous manual, semi-autonomous or fully autonomous. In a remote operation application like space exploration, military operations, automated security, search and rescue, etc. human does not have a direct visual awareness of environment to perform the required tasks and hence a tight interaction between human and robot is required for effective cooperation; which raises an interaction dilemma. Here robot (operating in remote environment) can be in a better position to react locally to remote environment and must refuse erroneous human commands which may result in collisions into obstacles; however, due to its limits ontologies, the robot requires human assistance on task such as object recognition and decision making. To overcome this interaction dilemma, appropriate role is used to exploit the capabilities of both the human and robot along with natural and effective modes of interactions. Hence the traditional master slave relationship is refined to a model of human as cooperator, supervisor, or teacher, rather than just master controller of the robot. A slave robot is modelled as an active assistant/ partners, subordinate, or learner of the human supporting perception and cooperative task execution.

Seamless is flexibility in human control in interacting with a robot is different situations and the adaptability of robot autonomy in response to human control. Here robot autonomy means the ability of a robot to act efficiently without any human interventions; the robot is autonomous means that the robot is thoroughly self-governing and capable of complete self-planning and self-control and it is expected to be able to operate with some level of capabilities in the absence of human supervision or management for a defined period of time. Hence flexibility means the ability of perform different aspects of HRS task easily by the human and adaptability means the adjustments to robot autonomy for performing task and robot should be able to carry out its processes irrespective of disturbance in the task environment. Hence, both human and robot will work together more coherently to ensure a high level of system performance and the satisfaction of task demands. Here a tele-robotic system is considered where the robot is not directly tele-operated thought out the complete work cycles, but can operate in continuous manual, semi-autonomous or autonomous modes based on situation (Kai et. al., 2008).

1.2 **Higher robot autonomy needs low levels of HRI**:

(Hui-Min et. al., 2007) termed integrated sensing, perceiving, analysing, communicating, planning, decision making and acting/executing as Robot Autonomous Capabilities (RACs), and also considered that higher autonomy of robot need lower Human intervention (HI). Level of Autonomy (LOA) corresponds to the HI axis of framework and it is higher when the corresponding metrics yield higher scores. The Higher HI score indicates that the RACs are performed by UMS to higher extents, i.e. LOA is high when RACs are performed by UMS to a higher level. The Authors also considered Contextual Autonomous Capability (CAC) Model for Unmanned systems which consider three aspects, i.e. mission complexity (MC), environmental complexity (EC) and human independence (HI). The Authors considered various modes of Unmanned System operation, which is the human operator’s ability to interact with UMS to perform the operation assigned missions in four modes i.e. fully autonomous, semi-autonomous, tele-operation, and remote control.

1.3 **Comparing both for considering levels of Robot autonomy**:

(Hui-Min et. al., 2007) considered five levels of autonomy based on the degree of human involvement, i.e. remote control; tele-operation; human directed level; human aided level, and autonomous level. Similarly (Kai et. al., 2008) also have five levels of based on robot and human interactions, i.e. Master Slave; Partner-Partner; Teacher Learner; Supervisor-Subordinate; and fully autonomous. Both can be resulting similar meaning as shown below.

Table : 1 Comparison of interactions for considering levels of Robot autonomy

	Kai et. al., 2008	Hui-Min et. al., 2007	
Master-Slave	To let the robot mimics the human actions exactly in performing a task.	Remote control level 1	The operational case with an unmanned system afforded neither self-determination nor independent. All sensing, preserving, analysing, planning, and decision making is done by a human, human direct all unmanned system actions from the human frame of reference; the case of maximum human influence over unmanned performance.
Partner-Partner	To let the robot supports the human perception, action and intention in performing a task.	Tele-operation level 2	The operation case with an unmanned system performing out of the direct observation of the human controller requiring the unmanned system to sense the environment and report its state of the human; all analysing, planning and decision making are done by the human; most perceiving is done by the human; human directs all unmanned system actions from the machine frame of reference
Teacher-Learner	To let the robot learns how to perform a task from the human	Human directed level 3	The operational case with an unmanned system performing out of the direct observation of the human controller requiring the unmanned system to sense the environment and report its state of the human; most analysing, planning and decision making are done by human, perceiving and acting is shared between the human and unmanned system
Supervisor-Subordinate	To let the robot performs a sequence of tasks planned by the human	Human aided level 4	The operational case with an unmanned system performing out of the direct observation of the human controller requiring the unmanned system to sense the environment and report its status to the human; analysing, planning, decision making is shared between the human and the machine; the most perceiving and acting is done by the unmanned system

Fully Autonomous	To let the robot performs a task independently for the human.	Autonomous level 5	The operational case with an unmanned system afforded the maximum degree of independence an self-determination within the context of the system's capabilities and limitations,; the case of minimum human influence over unmanned performance, an unmanned system performing out of the direct observation of the human controller; requiring the unmanned system to sense its environment and report its state to the human; all perceiving and acting are done by the machine; most analyzing, planning and decision making are conducted by the unmanned system, negotiation and collaboration may be performed by the human.

(Kai et. al., 2008) considered that these five roles can lead to four interaction modes. These include: Manual mode; Exclusive Shared Mode; Exclusive Traded Mode; and Autonomous Mode.

Manual mode is used for the task that are best performed by the human, Robot takes on initiative except to stop when communications break down and human is responsible for every action taken by the robot; robot can be configured to take the basic initiative to protect itself by assessing its status and surrounding environment to decide if the command issues by the human are safe. Here the Master-Slave relationship is mainly used.

Exclusive Shared Mode is used for the tasks that require constant or frequent cooperation between the human and robot, the human and robot can control different aspects of the system concurrently and the robot has similar basic competence as in the exclusive traded mode. Though the robot only handles the low level task, the human may intermittently control the robot by choosing a command loop. Human may control some variables while the robot performs the other executions. Here Partner-Partner relation is mainly used.

Exclusive Traded Made is used for tasks that require temporal cooperation between the human and the robot, the control is delegated to the robot while the human typically assumes a monitoring role; and human may resume (trade) the control from the robot when it encounters any problems. The robot’s competence includes capabilities to choose its own path, responds intelligently to the environment, and to accomplish local goals using a sequence of behaviours. Here, Supervisor-Subordinate relationship is used.

Autonomous Mode is used for tasks that are best performed by the robot, here the human is only responsible for relative long term plan; and once the control system is set up, essentially all the robot control is autonomous, and a human can monitor but cannot influence the low level process.

As per (Kai et. al., 2008) Teacher-Learner relationship can be adopted during Exclusive Shared mode and Exclusive Traded Mode. Also, these four modes are similar to remote control; tele-operated; semi-automated; and automated modes. Following figure shows final Robot Autonomy Spectrum.

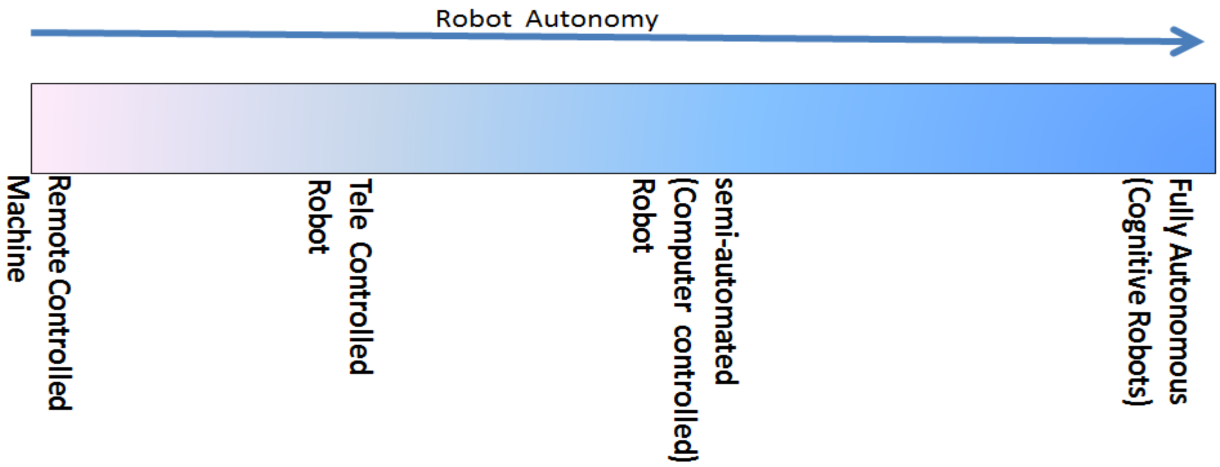


Figure 1: Robot Autonomy Spectrum

2.0 **Robot autonomy Spectrum detail**:

As seen during last section that during robot autonomy spectrum robots will have four main types i.e. remote Controlled machine, Tele- Controlled Robots, Semi-Autonomous Robot, and Fully Autonomous Robots. Following section will explain these levels in detail.

2.1 **Remote controlled machines**:

Here human operator is in the vicinity of the robot and operator will do all sensing, planning, acting operation and machines are just to follow the humans; this causes many problems of safety and many time operators are crushed under the machine; and many countries are planning laws to prohibiting work machine remote control (Jari et. al., 2007). The machine does not support any primitives and humans are needed continuously (Hui-Min et. al., 2007). This gives rise to a need for operating robots from a distance so that operators are safe which leads to tele-operation.

2.2 **Tele-operation controlled Robot**:

Tele-operation means doing the work at a distance, but there is no clear meaning of work and distance; Traditionally tele-operation is used in application where normal on board manual operation/control cannot be used or where it is too hazardous or expensive; for example, handling nuclear materials (dangerous), control of small models (impossible) and space and underwater exploration (hazardous and expensive) (Lichiardopol, 2007). Similarly, the construction industry is also considered as dangerous (Jain and Phadtare, 2013).

During tele-operation operator, the robot has master and slave relation. Human operator (Master) control robot (slave); system has two main components, i.e. control module (cockpit, which is local and have display and control mechanism) and tele-manipulator (Slave robot remote location and has sensors, effectors, power and mobility in case of a mobile robot) (Robinr, 2000; Lichiardopol, 2007). The control interface can be a joystick; virtual reality gear; or any number of innovative interfaces. A Tele-operator cannot see directly what the remote is doing and hence sensors which acquire information about the remote location; display technology for allowing the operator to see the sensor data; communication link between the local and remote are critical components of a tele-system. Tele-operation is a popular solution for controlling remotes as AI technology is nowhere near human levels of competence, especially in terms of perception and decision making. Human control has many advantages as humans can isolate an object of interest; can perform dexterous manipulation which is difficult to program manipulator. (Robinr, 2000).

Tele-operation is best suited for application where:

- Tasks are unstructured and not repetitive.
- The task workshop cannot be engineered to permit the use of industrial manipulators.
- A Key portion of the task intermittently require dexterous manipulation, especially hand eye coordination.

- Key portions of the task require object recognition, situational awareness, or other advanced perceptions
- The needs of the display technology do not exceed the limitation of the communication link (band width, time delays)
- The availability of trained personnel is not an issue. (Robinr, 2000)

However, tele-operation is not an ideal solution for all situations, especially during repetitive tasks that are boring (Robinr, 2000; Bernold et. al., 1990). For example, using joysticks to drive a radio controlled car after a few hours it tends to get harder and harder to pay attention and also trying to control the car while only looking through a small camera mounted in front, the task becomes much harder due to limited field of view and there is no peripheral vision and the camera may not be transmitting new images very fast because the communication link has a limited bandwidth hence view is jerky. People experience cognitive fatigue and their attention wanders and they may even experience headaches and other physical symptoms of stress. Even if visual display is excellent the tele-operator may get simulator sickness due to the discordance between the visual system, saying the operator is moving and the inner ear saying the operator is stationary. Another disadvantage of tele-operation is that it can be inefficient to use for applications that have a large time delay which can result is the tele-operator giving a remote a command, unaware that it will place the remote in jeopardy or unanticipated event like a rock fall might occur and destroy the robot before the tele-operator can see the event and command the robot to flee. A rule of thumb or heuristic is that the time it takes to do a task with traditional tele-operation grows linearly with the transmission delay. Researchers have made some progress with predictive displays which immediately display what the simulation result of the command would be. This will also happen in unmanned aerial vehicles (UAV) and though advanced prototypes of these vehicles can fly autonomously but take-off and landings are difficult for on board computer control.

Another practical drawback of tele-operation is that there is at least one person per robot or even more. The predator unmanned aerial vehicle has been used by the US for verification of Dayton accords in Bosnia; one predator requires at least one tele-operator to fly the vehicle and another tele-operator to command the sensor payload to look at particular areas. Other UAV have a team composed of up to four tele-operators plus a fifth team member who is specialized in takeoff and landing. This tele-operator may have over a year of training before they can fly the vehicle. Hence in case of UAV tele-operation permit a dangerous, important task to be completed but with high cost in manpower. (Robinr, 2000)

Adaptation of video technology and force feedback to tele-operation made first tele-presence systems possible and computer technology brought the advanced control loops into remote (tele-operator) end of system and lastly virtual reality into tele-operation. (Lichiardopol, 2007). This provides a more natural interface to the human however it is costly in terms of equipment and requires very high bandwidth rates. It also still requires one person per robot though it is better than traditional tele-operation but a long way from having one tele-operator control multiple robots. (Robinr, 2000). Hence to control more robots and to get better efficiency from operator semi-autonomous control is needed.

2.3 **Semi-autonomous Computer control Robot**:

Semi-autonomous control is another line of research in tele-operation and also known as supervisory control where the remote is given an instruction or portion of a task that it can safely do on its own. There are two means of semi-autonomous control, i.e. continuous assistance (shared control) and control trading (Robinr, 2000).

In continuous assistance systems, the tele-operator and remote share control, the tele-operator can either delegate a task for the robot to do or can do it via direct control. If tele operator delegates the task to the robot the human must still monitor to make sure that nothing goes wrong, it is more useful for tele-operating robot arms in space. The operator can relax while the robot arm moves into the specified position near a panel, staying on alert in case something goes wrong. Then the operator can take over and perform the actions which require hand eye coordination. Shared control helps the operator avoid cognitive fatigue by delegating boring, repetitive control actions of the robot and it also exploits the ability of a human to perform delicate operations. However, it still requires a high communication bandwidth (Robinr, 2000).

During control trading the human initiates an action for the robot to complete autonomously and human only interacts with the robot to give it a new command or to interrupt it and change its orders. (It will be like a parent giving a 10 year old child a task to do and as parent knows what the child is able to do autonomously they have a common definition and parent doesn’t care about the details of how the child cleans the room.). Control trading assumes that the robot is capable of autonomously accomplishing certain tasks without sharing control. The main advantage is that in theory the local operator can give a robot a task to do, and then turn attention to another robot and delegate a task to it and hence single operator could control multiple robots because they would not require even casual monitoring while they were performing a task (Robinr, 2000).

Supervisory control also reduces the demand on bandwidth and problem with communication delays; Data such as video images need to be transferred only when the local is configuring the remote for a new task and not all the time. As the operator is not involved in directly controlling the robot a 2.5 minute delay in communication is irrelevant and robot either wrecked itself or it did not; during control trading it assumed that the robots have actions that they can perform robustly even in the unexpected situation however it may or may not be true, hence it needs artificial intelligence (Robinr, 2000). Hence semi-autonomous control can handle multi robots also.

2.4 **Fully autonomous Robot**:

Autonomous system is a system which resolves choices on its own; decision making processes may be simple, but the choices are made locally (whereas automated system follows a script, although a potentially sophisticated; and when it encounters, an unplanned situation, it stops and waits for human help); choices may be either be made already and encoded in some way, or will be made externally to the system.

Main attributes of such autonomy for a robotic system include the ability for complex decision making; including autonomous mission execution and planning; ability to self-adapt as the change in the environment in which it operates; and the ability to understand system state and react accordingly (Rob et. al., 2010). During fully autonomous mode machine operation wherein the machine accomplishes its assigned mission within a defined scope, without human intervention while adapting to operational and environmental conditions (Clothier et. al., 2013).

In case of high level robot autonomy many robots will act in a team (Jenay et. al., 2014). As per (Robinr, 2000) collection of two or more mobile robots working together are known as teams or societies or multi agents. These multi agent teams are needed for many reasons i.e. to cover a large area, to replace single large robot by cheap robots working together for more cost effective. Swarm robots are becoming more popular which refer a large number of robots working on a single task. Redundancy is another motivation for multiple robots which, if one robot fails or destroyed the other robots can continue and complete the job with lesser speed or efficiency.

Teams can be heterogeneous teams have at least two members with different hardware or software capabilities, whereas homogeneous teams have all members identical. Members can be homogenous for one portion of a task by running identical behaviours; then become heterogeneous if the team members change the behavioural mix or tasks.

Control during multi agent can fall on a spectrum bounded by centralized control and distributed control regimes. During centralized control the robots communicate with a central computer which distributes assignments, goals, etc. to the remote robots which are semi-autonomous with the centralized computer playing the role of a tele-operator in a tele-operated system(Robinr, 2000). (Jari et. al., 2007) considered GIM test platform for multiple machines, remote control platform that allow the testing and development of a variety of generic systems with real work machines. The platform offers different types of machines that should be operable from (on board, locally or remotely) and machines are equipped with on board the computers which allow the development of autonomy as well as assistive functions for tele-operation. Here software architecture is completely distributed which allow the design of any type, as applications varying from direct tele-operation to fully featured autonomy and software can serve as a basic infrastructure for future GIM research projects (Jari et. al., 2007). In Distributed control each robot makes its own decisions and act independently(Robinr, 2000). These robots can be standalone or networked, Basra KOKEN, and Gyula MESTER (2015) observes that cloud robotics help robots in both form i.e. standalone or networked robots. While standalone robot can be benefited by cloud in terms of computational power, storage capacity and memory, whereas networked robots can make networks, share information through cloud and can perform collaborative works.

Co-operation in multi robot refers to how the robots interact with each other in pursuing a goal and robot can have some time active co-operation (by acknowledging one another and working together; however, sometimes they may not communicate) or commonly non active co-operation (they individually pursue a goal without acknowledging other robots but cooperation emerges). Cooperation in terms of robots working together on a task is easy to think and another aspect of cooperation is physical co-operation where robot physically aids each other or interacts in similar ways. Marsupial robots have physical cooperation, especially during deployment and docking. Re-configurable robots have a special type of cooperation. For example, in Toshio Fukuda called CEBOT for “cellular robot system”, small identical robots hook up to form a useful robot. Co-operative mobility is another aspect of reconfigurable robots; here one robot might come over and help another robot is trouble.

If all robots in collection work on attaining the same explicit goal, then they are said to share a single goal versus having individual goals.

During emergent social behaviour when a large number of robots are working under distributed control social rules may have an impact on overall team performance. During this robot may function with three types of co-existence with other robots. These include ignorant co-existence; informed co-existence; and intelligent co-existence. During ignorant coexistence robot coexisted in a team, but did not have any knowledge of each other. A robot treats another robot as an obstacle and each robot have the equivalent of a move-to-goal and avoid-obstacle behaviour. During informed co-existence the robots were allowed to recognize each other and given a simple social rule governing inter-robot interactions and hence along with move-to-goal and avoid-obstacle a third behaviour was created for avoiding robots. If a robot is detected, another robot would stop and wait for time and if the blocking robot was still in the way after the robot would turn left and then resume moving to the goal. During intelligent co-existence here social behaviour is to avoid robot was replaced with another heuristic i.e. the robots were repulsed from other robots, but as it moves away, it tries to move in the same direction as a majority of other robots (each robot broadcast its heading over a radio transmitter to compensate for the inability to recognize each other by visions or sonar so that is not considered communication).

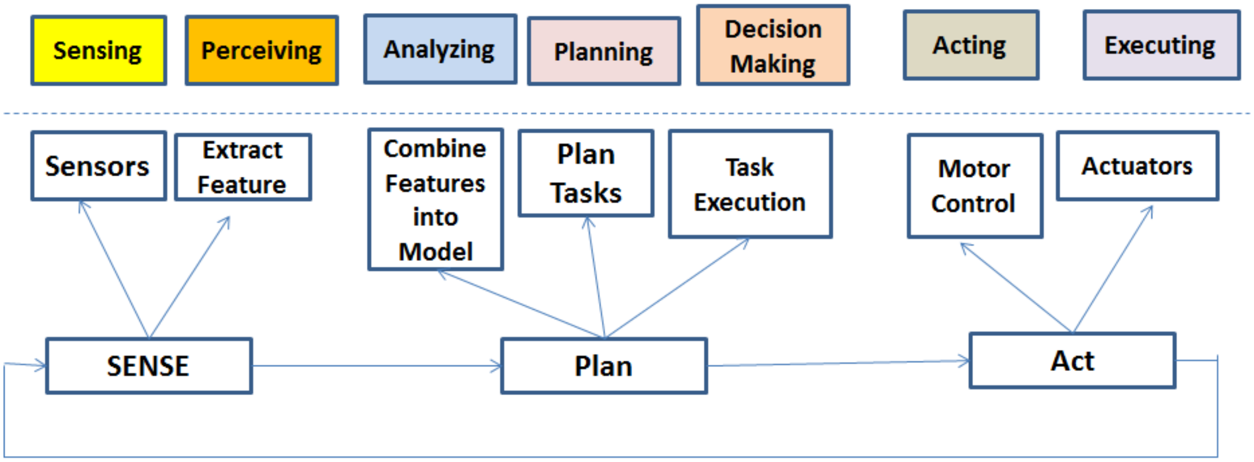
During team work robot get frustrated, then can be motivated by two internal motivations. These include: robot impatience; and robot acquiescence. The more frustrated a robot gets with another robot’s performance, the higher the impatience associated with that task. Similarly the more frustrated a robot gets with its own performance for a task, the higher the acquiescence. If the frustration threshold exceeds then the robot either takes on unfinished task or abandons its current task and change behaviour (Robinr, 2000).

3.0 **Role of human and Robots during Continuum of Robot autonomy**:

Robot Autonomous Capabilities (RAC) (Hui-Min et. al., 2007) and Horizontal decomposition of Basic Robot Primitives i.e. SENSE, PLAN, and ACT during reactive architecture (Robinr, 2000) are having similarities as shown below.

Root Autonomous Capabilities (RAC)

Source : (Hui-Min Huang, et al 2007)



As per Horizontal decomposition of SENSE, PLAN, ACT

Source: (Robinr Murphy, 2000)

Figure: Comparison of RAC and Horizontal decomposition of SENSE, PLAN, ACT

The Role of human and robot is considered based on these Robot Autonomous Capabilities along with communication during Continuum of Robot autonomy, as shown in following table.

Table: Role of Human and Robots during various stages of Robot autonomy spectrum

Stages of Robot Autonomy Spectrum	Role of Human and Robot							
	Sensing	Perceiving	Analysing	Planning	Decision Making	Acting	Executing	Communicating
Fully Autonomous (Cognitive Robots)	All Robot	Most Robot	Most Robot	Most Robot	Most Robot	All Robot	All Robot	Most Robot
Semi-Automated	All Robot	Most Robot/	Shared	Shared	Shared	Most Robot	Most Robot	Most Robot

(Computer controlled robot)		Shared						
Tele Controlled Robot	Shared	Most Man	Most Man	Most Man	Most Man	Shared	Shared	Most Robot
Remote controlled Machines	All Human	All Human	All Human	All Human	All Human	Most Human	Most Human	Most Human

4.0 **Conclusion**:

Robot Autonomy Spectrum is a continuous increase in level of robot autonomy and at one extreme end remote controlled machine is there which have no automation, but operators have to perform almost all tasks of controlling; whereas on the other side of spectrum robots are fully autonomous and human intervention is very minimum or almost nil. As this spectrum has four stages i.e. remote controlled machine, tele-operation controlled robot, semi-autonomous controlled robot, and fully autonomous robot. During these first two stages individual robot is controlled, whereas during semi-automated and fully autonomous multi robots can be controlled. During the semi-autonomous controlled robot, commands can be in two ways, i.e. continuous assistance (shared control) and control trading. Developer of robot firms can consider these stages for development of the robot so that these robots can be adopted by various construction firms smoothly and also at a reduced cost. As role of human and robot during this spectrum is given, may help both developers and users to decide about the training aspects to use the robot, as operators (those who uses robots) must learn how to handle robots in an incremental manner as direct use of fully autonomous robot may lead to mismatch in the construction industry as the product in the construction industry may not be designed for use of that type of robot.

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