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Human-robot interaction in the industry

Bachelor's thesis

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AALTO UNIVERSITY SCHOOL OF ENGINEERING PL 11000, 00076 AALTO http://www.aalto.fi	ABSTRACT OF BACHELOR'S THESIS	
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Abstract

Nowadays the industry needs to face more changes in production and needs to be more competitive. Therefore a new kind of robot has been making its way into many companies. These androids perform independently and learn both how to respond to the world and how the world responds to actions they undertake. Called 'Collaborative Robots', they are characterized for being safe, easy to use and affordable.

The aim of this thesis is to carry out a research in the new world of collaborative robots and, in particular, in how they work in the industry side by side with humans.

On one hand the goal is to know the main features like safety as it is one of the main differences against the classical robots and the reason they are able to work alongside humans.

On the other hand, the target is to study the way they work in order to analyze the human-robot interaction putting forward a possible paradigm and a specific organization in the workshop so that every company can face the changing flow production in the assembly line finding an easy way for the worker to adapt the robot in every different task.

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1 Introduction

For years, robot systems have been human-centric. The human receives information, selects an action, and finally makes a decision. However, this relationship between the robot and the human is often not efficient or effective. The concepts of “Robot as a tool” and “human as a controller” have been the problem or the limitation in the evolution of robot science (Fong, 2001). In order to solve these issues, nowadays collaborative robots are in the industrial market as a possible settlement. They come from the Northwestern University. A group of professors with the help of automotive manufacturers designed this kind of robot at the Laboratory for Intelligent Mechanical Systems. Their main feature is to work side by side along humans. So they are built to help industrial workers as a guide in a particular task. In order to achieve this collaboration they are completely safe, lightweight and easy to command in any task.

1.1 Background of the robotic framework

Along the years, robots have been considered tools. This means that a robot is just a device that receives orders and carries them out. This is the main limitation; Robots don’t have freedom to decide which way to go. If a robot has an issue, it doesn’t make a decision on its own; it needs to wait for an order to keep moving and carry out the task. Robots should now function as active partners, rather than passive tools.

On the other end of this relationship we have the ‘human as a controller’. Here, humans have the information necessary to make decisions, controlling the tasks a robot then needs to carry out. If the model of having “robot as a tool” is troublesome, “human as controller” is likewise problematic. The first issue is that “it consumes valuable human resources and may awkwardly bind the system’s capability to the operator’s skill” (Fong, 2001). Furthermore, “the quality of the human-machine connection significantly impacts performance and this is not good for the efficiency of the system” (Fong, 2001). Finally the third way in which human-as-controller causes problems is the imbalance in roles. “Whenever the human is in control, he has reduced capacity for performing other tasks” (Fong, 2001).

1.2 The birth of a new class of robots

After years of limitations in the robotic framework, the collaboration between humans and robots is becoming more common inside several production lines with the help of a new breed of androids called collaborative robots, which are free of many safety constraints and easy to use.

Since the objective of the robotics world is to build control systems, which are able to carry out tasks in a comfortable way in difficult environments, the manufacturing needs a new approach; instead of seeing the human as a controller, now the framework has changed to seeing the human as a collaborator. This change means that instead of having a person giving orders to a subordinate robot, the human and the robot engage in dialogue to exchange ideas, to ask questions, and to solve differences.

In this new approach, instead of the person having all the control, the robot is acknowledged more importance and together, they can exchange points of view on the way to achieve a particular goal. This is the birth of the new robot idea. In this new control model, the worker and the android make a team working side by side in order to achieve common goals (Koeppe, 2014).

1.3 The importance of Collaborative Robots

Since the collaborative robots have entered the industry world, the way of working in this area has changed and the workers have had to adapt to a new working style, leaving room to evidence the benefits of collaborative robots. Some characteristics of this new kind of android are presented in the following lines.

1.3.1 Humanlike and Cage-Free

The old robots that used to need safety constraints are far from this new kind of androids, which disregard any kind of fences. Therefor, the main feature of collaborative robots is that they can operate in the human workspaces without safety fencing. This kind of robot is cage-free. Furthermore, since these robots have to work alongside humans, they must have similar characteristics with humans. For that reason collaborative robots are flexible and dexterous. There are single arms or dual arms, with six or seven axis and this allows them to do the same movements as humans.

1.3.2 Kinematic Redundancy

In the robotics market, there are six axis and seven axis arms. The second type has a kinematic redundancy; this means that it has seven degrees of freedom, which allow the worker to control it in order to get the arm of the robot out of the way of other objects or people. “It’s like holding your grasp in one location, and still being able to swivel your elbow around to place it on the arm rest” (Anandan, 2013). Most of the lightweight robots are six axes, which means that they are not kinematic redundant, nevertheless they are well designed so there are no difficulties to work with them alongside humans. We can therefor appreciate that kinematic redundancy is not extremely necessary, but rather useful when you have a crowded space.

1.3.3 Classic robots versus Collaborative robots

In order to have a visual idea of the difference between the normal industrial robots and the new collaborative robots, in the following Table 1 are enlisted the highlights of each type of robot.

Classical industrial robots	Collaborative robots
Blind and unaware of surroundings	Ability to see and understand people and environment
Dangerous	Safe

Compete on precision and repeatability	Focused on flexibility and ease of use
Task must be restructured for that solution	Task done just as a human does it
Requires components and integration	Fully integrated and self contained
Requires expert programmers	Can be trained by ordinary people
Expensive	Unbelievably inexpensive

Table 1. Comparison between classical robots and collaborative robots (Laplace)

However, collaborative robots and classic industrial robots are not competitors. Collaborative robotics is a new kind that means to be complementary to industrial robots.

2 Collaborative robots in the industry

Collaborative robots are every day being more common in the industry, changing all the preconceived thoughts about robotics. Their main feature is the ability to work safely alongside humans. In the following lines, an analysis of these androids, working in the assembly line of different companies, is carried out. There are many different robots in the next pages, but all of them have a common feature: they are collaborative robots and for that reason they are made to work alongside humans through their flexible and lightweight characteristics. As a result of that, they are extremely safe, which is the main thing that differentiates them from classic robots.

From and industrial framework, there is a classification in accordance with the level of collaboration between the robot and the human. This rating depends on the sensors installed in the robot, the kind of interface the robot uses to communicate with the coworker and the ease to program them (Olivier, 2013). In other words, we can take this rating as a classification of the best collaborative robots nowadays.

For one arm based systems, there is a ranking according to the level of collaboration from the left (best robot) to the right (worst robot).

Speedy-10 > Roberta > PROb 10 > Kuka > UR10 > Pf 400

For two arm-based systems, there is a ranking according to the level of collaboration from the left (best robot) to the right (worst robot).

Baxter > Workerbot > Nextage > Yumi

With the aim to highlight the main characteristics of these androids, three main features are taken into consideration (Table 2); First of all, there are one arm-based systems or two arm-based systems. Secondly, the robots are classified according to the portability of the body and finally, they are placed in order from the ones who can handle the most payload to the ones that can handle the least payload.

Collaborative robots comparative		
Arm design	**1 arm based system**	**2 arm based system**
Portability	**Static based system (By hand)**	**Mobile based system (Mobil platform)**
Payload	Iwwa (7 axis)	Workerbot (7 axis each arm)
	UR10 (6 axis)	Baxter (7 axis each arm)
+	Speedy-10 (6 axis)	Nextage (6 axis each arm)
	Roberta (6 axis)	Yumi (7 axis each arm)
	PRob 10 (6 axis)	
-	Pf 400 (4 axis)	

Table 2.Comparative according to number of axis, portability, payload and arm design system (Automation), (ABBRobotics, 2015), (RethinkRobotics) (Olivier, 2013)

In the following chapters we may find the particular descriptions of each robot presented in the comparative of the previous classifications.

2.1.1 The versatile light-weight robot arm

The main feature of this robot is the user-friendly online software for programming. It is made to make customers' lives easier. The robot has an easy programming system that allows the worker to teach it in a fast and simple way. It works with HTML5 and Java Script to program the robot. The other interesting thing about this new collaborative robot is the built-in 2-finger gripper (see Figure 1). The modular end effector is made of a soft material, which makes it safe for humans. Safety is again an important feature in the robot. Furthermore, the fingers are easy to change using only 2 screws.

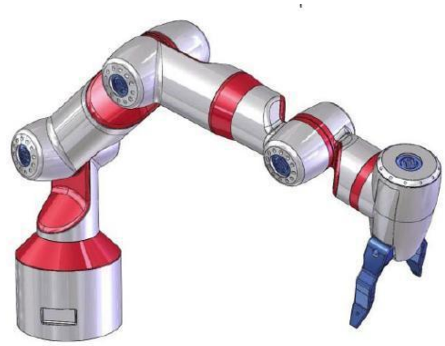


Figure 1. The versatile lightweight robot arm (PRob 1R from f&p personal robotics)

The PRob 1R weighs only 10 kg and it is able to work in a range of 700 mm. On the other hand, he can stand a payload of 1.5Kg. Therefore the most important features of PRob Collaborative Robot are (Olivier, 2013):

- "Easy to program and monitor "
- "Built-in gripper and tool changer "
- "Possibility to change gripper configuration "
- "Learning capability"

2.1.2 The flexible and efficient robot arm

Roberta is a 6-axis collaborative robot. It's designed with the aim to build a really lightweight robot capable to move along the working area without any difficulties (see Figure 2). With a weight of 19.5 kg, it can handle a payload as high as 8.0 kg.

Figure 2. The flexible and efficient robot arm (Roberta from gomtec)

Thanks to its several joints the robot is able to do many movements in order to avoid any object and at the same time, reach almost every point nearby without passing through singularity points.

Roberta is easy to program, as it's enough simply to demonstrate the desired task for the robot to learn it. This way, the coworker is able to commission any task to the robot without any knowledge of programming and only going over the movement for a couple of minutes. It is important to know that Roberta presents several integrated safety concepts. It has characteristics such as safety nodes on each axis and dual safety nodes for overall robot monitoring functions.

In conclusion the main Characteristics of this robot from gomtec are (Olivier, 2013):

- "Lightweight"
- "6 degrees of freedom without singularity points"
- "Good payload to structural weight ratio"
- "Inexpensive"

2.1.3 The Swiss lightweight robot

Speedy-10 is really similar to UR10 (see Figure 3). It has a really intuitive interface that allows the employees to work more easily. The difference between the UR10 is that the speedy-10 uses an 18-bit absolute encoder and a KeMotion controller by KEBA. In other words the difference is in the control architecture and not in the physical body and joints.

Figure 3. The Swiss lightweight robot (speedy-10 from mabi)

The weak point of speedy 10 is that its axis system still needs to improve. Nonetheless, it offers high precision positioning for high-speed applications thanks to a high-resolution, absolute feedback encoder.

Furthermore, it's a kind of robot that outstands for its lightness, which comes very useful when moving through the shop floor.

To sum up, the main features are these (Olivier, 2013):

- "Lightweight design"
- "6-axis kinematics system with standard wrist"
- "High-resolution 18-bit absolute encoder"
- "High precision positioning"
- "Intuitive graphical user interface"

2.1.4 A flexible dual arm for small assembly

This dual arm robot has fourteen axes of freedom (seven in each arm) (see Figure 4). With the size of a small adult, it takes the same workspace as a human but it is still a really compact robot and it is easy for it to move through the work area, as well as to mount onto different workstations.

In the past this robot was massive and big, and with its evolution it has become one of the most important collaborative robots with a small size, lightweight and very compact.

In terms of the programming of this robot, it has a user-friendly interface with a screen where the worker can choose the variables and then by moving the arm, it can indicate the robot the desired task to carry out (ABB).

Figure 4. A flexible dual arm for small assembly (Yumi from ABB)

These are the main features (Olivier, 2013):

- “Harmless robotic co-worker for industrial assembly”
- “Human-like arms and body with integrated IRC5 controller”
- “Complements human labor with scalable automation”
- “Padded dual arms ensure safe productivity and flexibility”
- “Lightweight and easy to mount for fast deployment”
- “Agile motion based on industry-leading ABB robot technology”

2.1.5 The robotic co-worker

This new robot from Rethink Robotics is one of the most important ones in the world of collaborative robots. The main goal of this Baxter is to automate repetitive tasks in order to minor the workload of the human in an environment of high-mix production.

On one hand, it has a user-friendly interface making things easier for work. Furthermore, it is programmed by teaching, which means that the worker doesn’t need any knowledge of programming to control Baxter. On the other hand, the aim of the builders of this robot was to make an accessible tool for all the workers in the shop floor, which as a result provided a really manageable, lightweight based robot.

One of its important features is that it allows the robot's arms to pick up and place parts at any axis. Its "head" is an LCD screen that displays facial expressions (see Figure 5). The worker can decide the desired movement simply by manipulating its arms and demonstrating the task to carry out for some minutes (Robotics). Finally, Baxter can now benefit from the capabilities and flexibility of the 2-Finger Adaptive Robot Gripper. In other words this means that it's able to handle a large variety of parts at the same time without problems. This robot is considered one of the most important in this field, mainly for the quick evolution on its hardware and software and for the facility it represents for the worker.

Figure 5. The robotic co-worker (Baxter from Rethink robotics)

To sum up, Baxter has (Olivier, 2013):

- "No Programming: Rethink Robotics highlight that Baxter can be trained in minutes without in-depth programming knowledge".
- "No Integration: Being a complete system, Baxter requires no integration. Only minimal training to be able to teach tasks to the robot".
- "Works Intelligently: Baxter is designed and programmed to perform a wide range of manufacturing and production tasks".

2.1.6 The low-cost robot arm

Universal Robots was one of the first companies to get in the world of collaborative robots. Their robots consist of six-axis arms that allow them great flexibility to do a variety of tasks. They offer two products: the UR5 and UR10 that can handle 5 and 10 kilos respectively. Lately they have developed some innovations on their robots. One of them has a new encoder. With the help of this new encoder it's easier for the robot to recognize the position of its arm and consequently start the movement from a known coordinate.

Another innovation is the safety features on its robot. The robotic settings can be achieved by monitoring eight different safety functions and it allows the robot to operate at different speeds depending on the context.

For example, “the collaborative robot can run full speed when working in conjunction with the computer numeric control machine and slow down once it is working along humans outside the machine” (URobots, 2014).

Finally, like some other collaborative robots, it has 2-Finger and 3-Finger Adaptive Robot Grippers, and this helps the robot be more adaptive to different kind of tasks.

In short, universal robots have these features (Olivier, 2013):

- “Low-noise robots”
- “Energy efficient”
- “The programming is simple. You just have to move the arm and record points for the trajectory. The UR can be up and ready to work in less than an hour without further knowledge in programming”.
- “Also, their compact design and light weight give them good portability around the plant floor”.
- “Universal Robots can work with humans without risk. In case of collision, the robot delivers less than 150 Newton of force and this amount of force is acceptable according to the “force and torque limitation” set by the ISO Standard”.
- “Universal Robots’ starting price is pretty low. They can also be customized for the client’s needs”.

2.1.7 The quality inspector

Workerbot is a robot from pi4_robotics, a company specialized in inspection systems. It has two arms of seven degrees of freedom each. Although the robot has a standard size, it’s heavier than other robots. It weighs 500 kg, but it is easy to move due to its mobile platform (see Figure 6).

The main function of this android is visual inspection, reason for which it has 3 integrated cameras that can work independently and simultaneously: two inspection cameras with illumination and one optional time-of-flight 3D camera. This last one allows face recognition, so the robot will react to someone who is looking at it. This is the main feature of workerbot.

Finally, it has an LCD screen that displays facial expressions and it can therefore gauge the grip and force needed on the object it wants to grab. This allows it to hold an egg without cracking it (Olivier, 2013).

Figure 6. The quality inspector (workerbot from pi4_robotics)

2.1.8 The first collaborative scara robot

The main goal of this Scara robot is to work in laboratories or other areas of small size, so it must have a small footprint, in fact it can fit in the palm of your hand. Moreover, the product needs to be safe to work around, without any barriers to allow proximity of other workers as a collaborative robot. So it is extremely compact and safe (see Figure 7).

Figure 7. The first collaborative scara robot (pf 400 from precise automation)

In order to optimize its size the controller is inside the robot and it has a four-axis motion. In terms of programming, it's done by simply moving the robot by hand from the starting position to the end position, using a simple communication protocol, Ethernet interface.

The other features of the PF 400 are (Olivier, 2013):

- "Low-cost"
- "Quiet"
- "Lightweight"
- "Can be combined with a vision system"

2.1.9 The new lightweight robot

Iiwa is a robot from Kuka. The companies' aim is to build a lightweight robot, easy to handle for the worker and specialized in industrial tasks. In order to achieve these features, it is a dexterous and flexible robot. Furthermore, it has several sensors on its body, which make him a really sensible android capable to detect any human presence (see Figure 8). It's a seven-axis robot and it can handle a payload of over 10 kg. Its programming paradigm uses the mainstream programming language, Java. (GmbH, 2014). The result of all these features is that it can work in tight spaces and it can be integrated on assembly lines quite easily.

Figure 8. The new lightweight robot (iiwa from kuka)

2.1.10 The next generation of industrial robot

This robot has two arms of 6 axis each, and a mobile base. It has a human aspect (see Figure 9), so in its 2 degrees of freedom head there are two cameras and with their help the robot is able to achieve a precise positioning system and detect all human presence or any physical objects. With the help of two more cameras in its arms, Nextage can take pictures from different views and also build a 3D map. With the help of the 3D mapping and the software GUI, the worker can program Nexatge by moving its arms and indicating the desired movements.

Figure 9. The next generation of industrial robot (Nextage from kawada industries)

2.2 Safety of the worker

When robots and humans are sharing a common workspace, safety is one of the most important issues, especially with this kind of new collaborative cage-free android. Furthermore, the evolution of collaborative robots is moving at the speed of light and for that reason all the systems have to be in order and meet all the standards.

The latest robot safety standards that address human and robot collaboration are the following ones:

- ANSI/RIA R15.06-2012, *Industrial Robots and Robot Systems – Safety Requirements*,

- ISO 10218:2011, *Robots and Robotic Devices – Safety Requirements for Industrial Robots*.

Although the first is American, it's necessary to analyze it because it's an international process carried out with the help of the most important robotics companies of the world and for that reason it's considered an important standard. It was approved on March 28th, 2013. It has 160 Pages. "It's a revision of ANSI R15.06-1999 and provides guidelines for the manufacture and integration of Industrial Robots and Robot Systems with emphasis on their safe use, the importance of risk assessment and establishing personnel safety" (Titus, 2013). The ANSI/RIA R15.06-2012 comes from the internationals ISO 10218-1 and ISO 10218-2, and based on them it contains a global safety standard for the manufacture and integration (Marvel, 2014). The standard is based in the human-robot relationship and consequently is the insertion of the coworker in the interaction world during any industrial robotic task. Furthermore the standard refers to a new feature in collaborative robots called soft axis and space limiting technology. "Safety-rated software is used to control the robot motion so that restricted space can be more flexibly designed" (Titus, 2013). Several researches have exposed that this is essential to keep in the system design the floor space and cost (Anandan, 2013).

The classical robots used to be heavy robots, really dangerous and full of hazards. With the evolution of technology, robots have been changing to the point of the collaborative robots. In the following picture we can see these changes along the years (see Figure 10).

Figure 10. Evolution of collaborative robots in the industry framework

In the previous picture is shown that the point of the collaborative robots, and also the main difference between normal robots is the Collaborative operation. For that reason the standard defines this concept as “the state in which purposely designed robots work in direct cooperation with a human within a defined workspace” (Titus, 2013). Furthermore it establishes different types of collaborative operation, specifically four clauses that are defined in the next two tables.

In the first table (see Figure 11) four requirements for human-robot interaction tasks are identified, which allow workers to be in control of the robot without the need of having physical fences. Each robot has to satisfy at least one criterion to meet the standard. In other words, to carry out one of these four tasks without fences between humans and robots, the workspace has to fit with these characteristics. For every type of collaborative operation the robot cell has to meet the rule associated (Björn, 2014).

On the other hand in the second table (see Figure 12) there are the same four tasks, where the robot variables such as the speed of the arm’s robot, the distance between the worker and the collaborative robot or the torques and payloads are shown. In the last column there is the main risk reduction in order to know what the worker has to do to avoid the hazard.

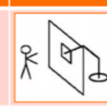
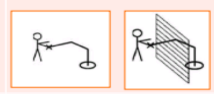
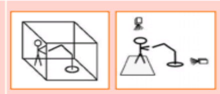
ISO 10218-1, clause	Type of collaborative operation	Main means of risk reduction	Pictogram (ISO 10218-2)
5.10.2	Safety-rated monitored stop (Example: manual loading-station)	No robot motion when operator is in collaborative work space	
5.10.3	Hand guiding (Example: operation as assist device)	Robot motion only through direct input of operator	
5.10.4	Speed and separation monitoring (Example: replenishing parts containers)	Robot motion only when separation distance above minimum separation distance	
5.10.5	Power and force limiting by inherent design or control (Example: *ABB Dual-Arm Concept Robot* collaborative assembly robot)	In contact events, robot can only impart limited static and dynamics forces	

Figure 11. Types of Collaborative Operation According to ISO 10218-1 (Björn, 2014).

In few words, these tables summarize the ISO standards that every company has to comply with to carry out collaborative robot tasks in their assembly lines.

To sum up, a sentence of the RIA’s director of standards development is a good way to understand this standard. Pat Davison said; “The standard mandates that a risk assessment be performed for each new robot application. Risk assessment looks at all the tasks that are going to be associated with that application over its lifecycle. It evaluates all the potential hazards associated with those tasks and determines ways to mitigate those hazards, either by reconfiguring the system so the hazard is eliminated, or adding safeguarding or other mechanisms that reduce hazard exposure”.

	Speed	Separation distance	Torques	Operator controls	Main risk reduction
Safety-rated monitored stop	Zero while operator in CWS*	Small or zero	Gravity + load compensation only	None while operator in CWS*	No motion in presence of operator
Hand guiding	Safety-rated monitored speed (PL d)	Small or zero	As by direct operator input	E-stop; Enabling device; Motion input	Motion only by direct operator input
Speed and separation monitoring	Safety-rated monitored speed (PL d)	Safety-rated monitored distance (PL d)	As required to execute application and maintain min. separ. distance	None while operator in CWS*	Contact between robot and operator prevented
Power and force limiting	Max. determined by RA⁺ to limit impact forces	Small or zero	Max. determined by RA⁺ to limit static forces	As required for application	By design or control, robot cannot impart excessive force

* CWS = Collaborative Work Space ⁺ RA = Risk Assessment

Figure 12 The Safety Functions of Industrial Robot Controller. Types of Collaborative Operation According to ISO 10218-1 (Björn, 2014).

2.3 Collaborative robots assembly line applications

After knowing several types of collaborative robots, companies and the importance of the safety in this world, in the following chapters is carried out an analysis in order to know what collaborative robots can do in their workspace. With a total of five main applications, collaborative robots are working alongside humans with the aim to change the way to work in the assembly line.

2.3.1 Pick and place

This kind of application is not only to carry out difficult tasks but also to carry out repetitive ones in order to support efficiency. Furthermore, the system is more exact than a human so this also increases accuracy and reduces shrinkage and the production line can still working without the human (Kaipa, Morato, Liu, & Gupta). The main advantages when using a collaborative robot instead of a human are that increases in productivity and the flexibility of the workspace and it is easier to program the robot so it is easy to adapt the pick and place for different tasks.

2.3.2 Computer numeric control

Thanks to the Computer numeric control, every manufactory can automate almost all the lines because the robot's arm can be quickly and easily deployed in new constellations, if the work flow changes. Intuitive software allows even the most inexperienced user to quickly grasp the basics of programming and set waypoints by simply moving the robot into position. With numeric control it's possible to relieve workers from dangerous work, lower the operating costs and improve speed and precision along with increasing the reliability and quality of the process. (Computer numerical control)

2.3.3 Quality inspection

In an automotive manufactory, after the assembly process, it's time to do the quality tests. In order to increase the consistency and to maintain high levels of product quality most of the companies install an inspection camera with the collaborative robot. So with a robot arm with vision camera can also be used for non-destructive testing and 3D measurements, further guaranteeing the quality of the products. To sum up, with the help of this application it's possible to avoid defective or faulty parts to be shipped, achieve more objectivity at the same time to lower operating costs and relieve workers from repetitive works as many collaborative robots applications. Moreover it ensures consistency and predictable quality of the process.

As an example, the water leak test is explained in the following lines. This test is very common in automotive assembly lines. In this test, as always, the worker has to work together with the machine. For the automated moisture detection an image processing system is applied to the robot. A thermography camera takes pictures of the interior of the car, after passing through the water tunnel. These photos are processed and wet spots can be detected. Then the worker has to take a decision about the analysis, according to the pictures. (Müller, Vette, & Scholer, 2014)

2.3.4 Packaging and palletizing

Automating the packaging and palletizing process, allows the production line to combat the costs of new product packaging and shortened product life cycles. Collaborative robot arms allow the companies to reprogram and redeploy as needed across their operations, maximizing flexibility, efficiency and productivity. This application is considered really similar to the pick and place because of the way that the robot works. Furthermore the advantages of automation the packaging and palletizing process are the same as pick and place.

2.3.5 Assembly

Finally one of the most important applications is the assembly. In almost every production line it's necessary an assembly task at some point of the process. In order to automate this task, the best option is to install a collaborative robot in the line. With this action the line reduces assembly times, increase production speed and improves quality. With the right adaptor mechanisms the robots can handle assembly of plastics, woods, metals or other materials. Specifically this kind of application is very common in the automotive industry in the production line where the goal is to assembly all the pieces of every car.

2.4 Sensors

When talking about collaborative robots, one of the most important features is that they are full of sensors along their body. This is needed because of their cooperation work alongside humans. Sensors allow having suitable safety, a good programming system and an easy-going way to handle with them. In the following lines there are the most important sensors in a collaborative robot cell and their features in order to understand how to program a robot or achieve a good interaction between human and robot. (Šekoranja, Bašić, Švaco, Šuligoj, & Jerbić, 2013)

2.4.1 2D Vision

As the name says, this sensor is based on a camera that is able to detect parts and coordinate the part position for the robot in two dimensions and then adapts its actions to the information it receives. In few words, 2D vision is basically a video camera that can perform different actions such as detecting movement or localization of a part on a conveyor. This kind of sensors can work because of the principle of intelligent vision sensor (Bouchard, 2014). In the following picture (Figure 13) the structure of this kind of sensor is shown. The first work of the sensor is taking the information about the image in front of it. After it, thanks to a control signal from the control unit, the image is sent to the parallel processing unit, where the information from the sensing unit is processed and finally the results are extracted and showed to the worker.

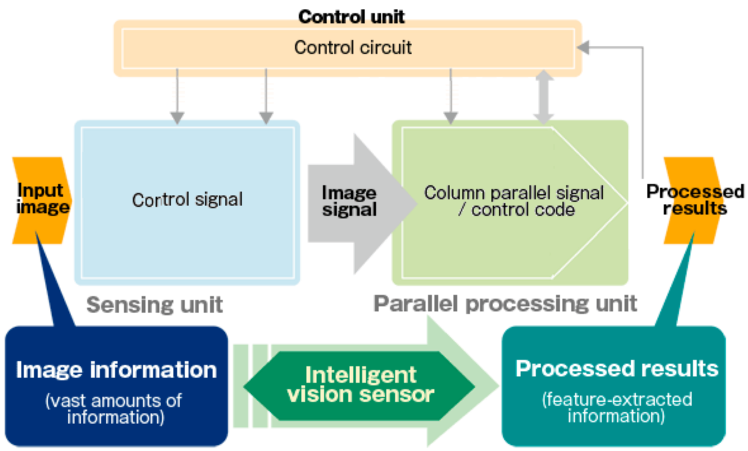


Figure 13. Internal structure of a 2D vision sensor.

2.4.2 3D Vision

This sensor is the evolution of the previous one so it's much more recent. A tri-dimensional vision system has to have 2 cameras at different angles or use laser scanners. This way, the third dimension of the object can be detected.

There are a lot of systems that can provide good results for 3D vision. In the following lines, the two most common in collaborative robots are presented; stereo imaging and structured lighting.

One of the most commonly used systems is based on stereo imaging. It uses two cameras to capture two independent images from two viewpoints. Relative depth of points in the scene can then be computed since the depth of each point is inversely proportional to the difference in the distance of the corresponding points and their camera centers. Then this can be used to generate a disparity map that visually provides 3D information (Bouchard, 2014). In the Figure 14 there is an example of the two cameras and result that provides in the right side; a depth map computed.

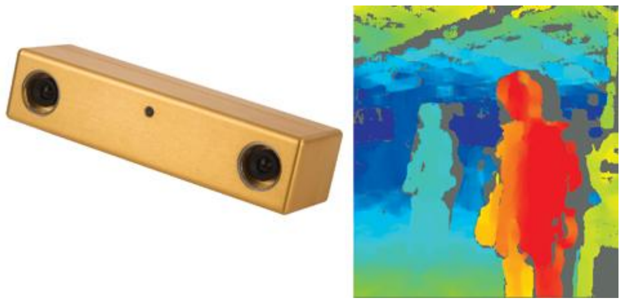


Figure 14. Stereo imaging camera (right side) and depth map (left side)

The same idea can be used with a single camera mounted on a robot and taking images from two or more locations.

On the other side, laser light is also a good choice for the 3D vision. To generate a 3D image using structured light, a camera is used to record the projected coherent laser beam reflected from the object's surface (see Figure 15). Since the geometry of the camera and laser combination is known, the coordinates of the projected laser beam can then be calculated by triangulation.

As the object or camera/laser system moves across the field of view of the object, X, Y, and Z coordinates are measured and used to generate a point cloud that represents the external surface of the object. This point cloud can then be projected onto a plane to produce a depth map.

Figure 15. The SP30 projector as a laser light camera.

2.4.3 Force torque sensor

The last two vision examples are not really common in hand guiding for programming, but they are common when taking information of the environment. Forces torque sensor is a kind of sensor that is really used in hand guiding, teaching and force limitation. The force torque sensor gives touch to the robot wrist and allows industrial welding robots to be taught via hand guiding. This sensor is able to monitor the motions of the "teacher", worker and robot can achieve a final common goal (ATIIndustrial). The force torque sensors are able to measure all six components of force and torque (see Figure 16).

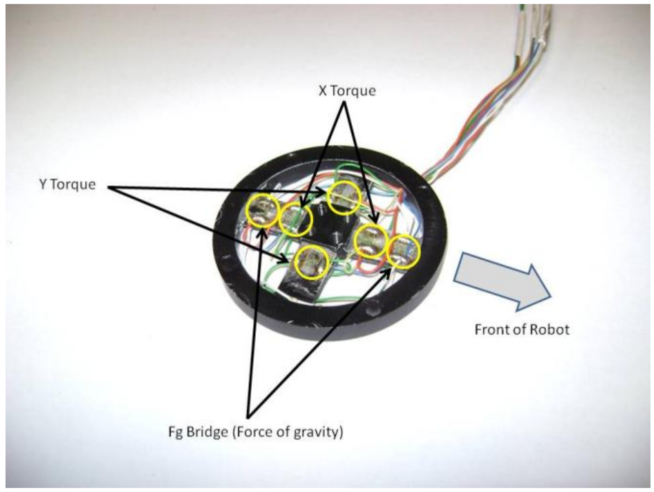


Figure 16. Distribution of the three Cartesian coordinates; x, y, and z (Force of gravity).

2.4.4 Collision detection sensor

If the purpose in a robot cell is for example to detect the force applied on the robot arm, to know if the robot is in collision with something or someone, this kind of sensor is the best choice to use. As the main applications of these sensors are to provide a safe working environment for human workers, the collaborative robots are most likely to use them.

Collision detection sensors can be by tactile recognition systems where if a pressure is sensed on a soft surface, a signal will be sent to the robot to limit or stop its motions (see Figure 17). It can also be by an accelerometer. In either case, when an abnormal force is sensed by the robot the emergency stop is released. In fewer words, this device can detect any collision before or during it (ATIIndustrial, Robotic Collision Sensors).

With the help of these sensors, safety is almost assured. Although, before the robot stops the worker will still be kicked by. It’s for that reason that safety sensors appear. These sensors can really appear in a lot of different shapes, from cameras to lasers. A safety sensor is designed to tell the robot that there is a presence around it. Some safety systems are configured to slow the robot down once the worker is in a certain area/space and to stop it once the worker is too close.

Figure 17. The ATI Collision Sensor with standard auto reset.

2.4.5 Part detection sensors

Many tasks in the assembly production line consist in picking up objects from an origin, and bringing them to another point. For that reason this sensors are really useful, because most of the times there is no way to know if the part is in the gripper or if you just missed it. Then, this sensor gives to the worker the feedback on the gripper position (Bouchard, 2014). For example, if a gripper misses a part in its grasping operation, the system will detect an error and will repeat the operation again to make sure the part is well grasped.

With the help of these part detection sensors, we can release the work of the human because instead of controlling the picking up action of the robot, the worker can do an independent task without worrying about the robot’s task.

2.5 Workspace distribution

An idea of some collaborative robots and their main function has been shown in previous pages. In the next pages is presented a focus on the functional part of these machines. Since they are made to work alongside humans, it’s necessary to carry out a workspace partition in the shop floor of the assembly line, in order to avoid interruptions between robot and worker. In manufacturing framework any mistake inevitably causes an interruption in the production process. The next proposed distribution is a flexible approach in order to be able to carry out any job without stops and consequently achieve a robust manufacturing system. For that reason, task partitions required for a robotic co-worker are described in the following lines to achieve a fluid interaction and cooperation between both parts. These physical human states are mapped into a meaningful topology shown in the following picture.

2.5.1 oP, iP, iCM and iHF

The first is ‘out of perception’. In Figure 18 corresponds the worker oP = True. The worker is “out of the perceptional ranges of the robot” (Haddadin, 2014), and for that reason the worker is not included in system part of the machine. This means that the human can only see the task process but he can't do anything during the process, because the robot doesn't take him into account and it is working autonomously.

On the other hand there is the one called 'in perception', iP = True in Figure 18, and it's the opposite of the previous one. In this case, the human "is in the measurement range of the robot, and thus its presence has to be part of the robot control" (Haddadin, 2014). So the robot has to take into account the presence of the worker in order to avoid collisions.

The third and the fourth ones are iCM and iHF. These last two indicate whether the robot is in collaborative or human-friendly behavior respectively. So iCM means that the collaboration between human and robot has to be considered; iCM = True in Figure 18.

In the other hand iHF, iHF =True in Figure 18, means that worker and robot aren't working together but human is in the workspace with the android and they have to share the space.

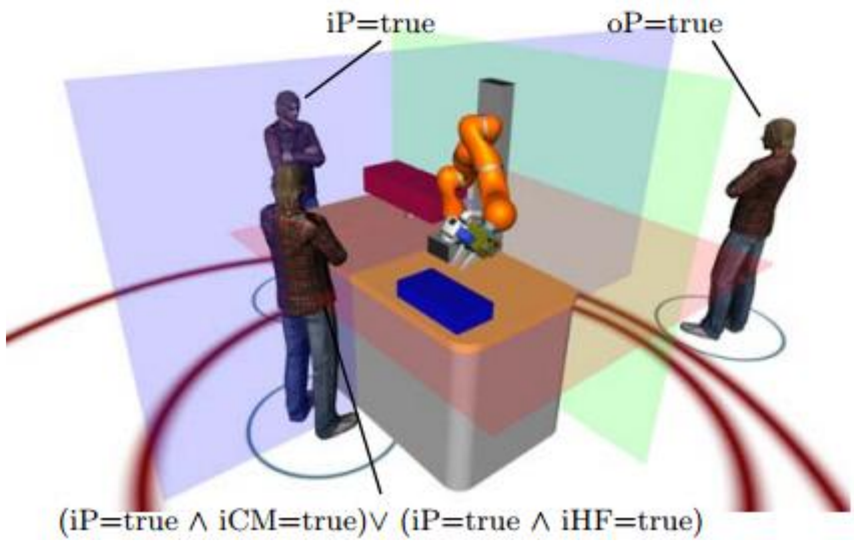


Figure 18. Physical human states and task partitions in the workspace (Haddadin, 2014).

Knowing these physical human states, the worker is able to control the robot depending on the case. In the case the worker is not in the same space of the robot, the worker can keep moving the productivity of the android without any danger. This situation remains until the worker enters in the workspace of the robot system. Then it's necessary to decrease the productivity of the robot and consequently a distinction between human friendly behavior (on the right side of the table in Figure 18) and the cooperative mode is required (on the left side of the table in Figure 18). Otherwise if the presence is lost while iP = true, the machine assumes a mistake in the system and stops the productivity waiting for a next advice.

2.5.2 Function modes

After the distribution of the workspace, there is an analysis of the four functional modes of the robot operation. It is considered the distinction between four major functional modes in a co-worker scenario (Haddadin, 2014):

1. "Autonomous task execution: autonomous mode in human absence".
2. "Human-friendly behavior: autonomous mode in human presence".
3. "Co-Worker behavior: cooperation with human in the loop".
4. "Fault reaction behavior: safe fault behavior with and without human in the loop".

Knowing the four functional modes, in the assembly production it's always possible to mix them and go from one to another without problems in order to streamline the process and increase production. In the first one, the human gives the task to the robot and it carries out the work without the help of the worker so without human presence. "The task is carried out under certain optimality criteria, such as cycle time, in order to maximize the productivity" (Haddadin, 2014).

The second one has some similarities with the first one, but in this case the human presence is in the workspace, so the robot has to share the space with the worker, but this last one doesn't do anything. These last ones are completely different with the third one, in which the worker and the robot have a common goal and they work side by side. For that reason in this mode a synergy of human and robot capabilities in an efficient manner is needed. The last mode is about the fault reaction behavior. It has the robustness concepts during autonomous reaction, as well as human-safe behavior.

In the following picture (Figure 19) there are all the combinations the worker can make to carry out a task. As an example, imagine the worker is carrying out a task in the autonomous mode, so he is not in the workspace of the robot because the robot is working alone. After this task his purpose is to carry out a different task that requires the collaboration to achieve the goal. Then, the worker has to go in the Collaborative mode. This change will be possible thanks an iP and iCM distributions, as it is shown in the Figure 19. This means that not only the human in the measurement range of the robot is required, but also that the collaborative intention should be taken into account. Only after applying these two distributions the worker will be able to achieve the Collaborative mode from the Autonomous one. (Haddadin, 2014)

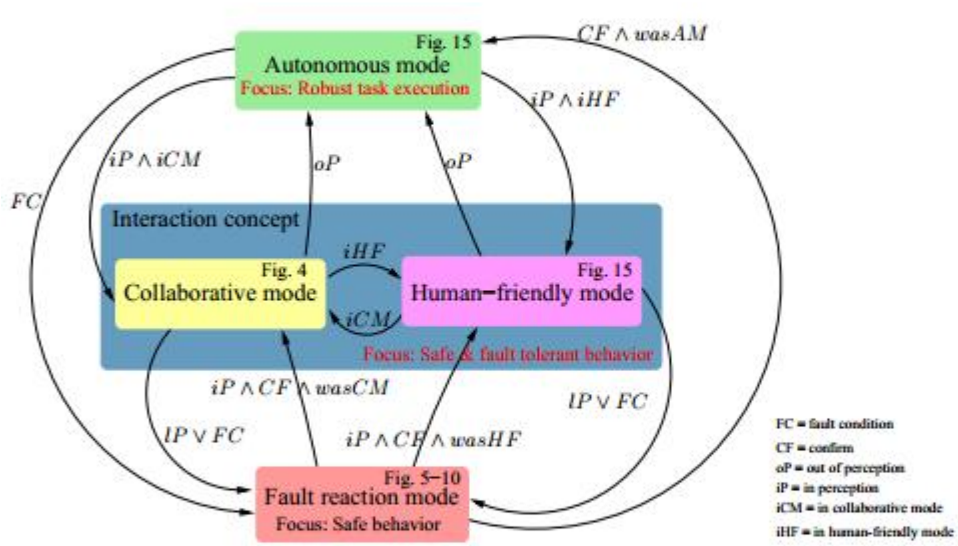


Figure 19. Functional modes for the DLR Co-Worker (Haddadin, 2014).

2.5.3 Interaction human-robot

Collaborative robots are based in the interaction between robot and human, and this is the main delicate task when working with these kinds of robots. This is the reason why multi-sensory information is required. The main physical collaboration schemes are "joint manipulation" and "hand over and receive" (Haddadin, 2014). In the cooperative assembly, one of the most typical actions is the interchange of tools and pieces between the worker and the robot. The following picture (Figure 20) shows the "hand-over" and "receive" implementation of the "DLR Co-Worker Central entity" (Haddadin, 2014) with its soft robotics features. The robot is equipped with joint torque sensors in every joint. Thanks to these sensors, the robot is able to perceive when it is losing load.

In order to avoid collisions it uses virtual walls with the environment through control schemes (see Figure 20). If the purpose is to achieve a sensitive conduct, it is essential to adjust some variables like velocity, disturbance residuals, trajectory generators, collision severity reaction strategies, etc.

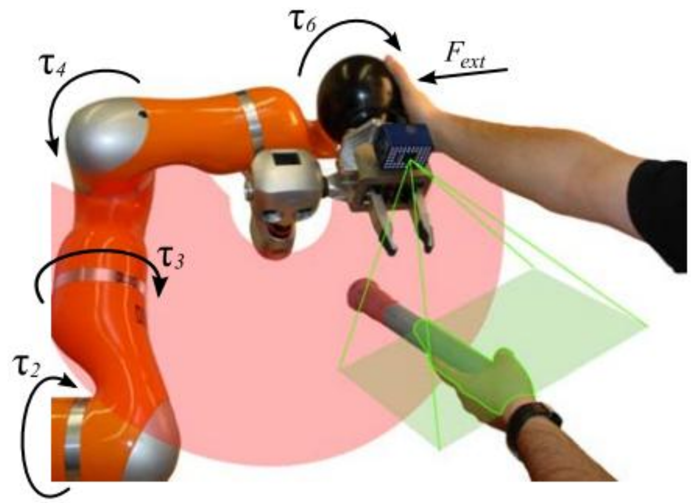


Figure 20. Modalities for multi sensor human robot interaction.

2.6 Programming by demonstration

When talking about assembly production issues from the collaborative robot framework, we always have to consider the worker as a very important part. This means that everything that a robot can do in order to make easier the worker’s tasks has to be implemented in the system. In order to understand this important issue from the collaborative robots, in the following lines there is an explanation of the Baxter robot as the best example to show the way to teach a collaborative robot and until where it is possible to reach with a robot like this.

Baxter is a robot from Rethink robotics, as it’s explained in the beginning of the thesis, and is a 3-foot tall (without pedestal; 12,95 cm – 16 cm with pedestal), two-armed robot with an animated face. It weighs 74,842 Kg without the pedestal and 139,799 Kg with the pedestal. With the help of the face, the communication between Baxter and the worker is much easier than a normal robot, and this is really important while co working.

The main feature of Baxter and also the definition of a collaborative robot is that it can learn. So any worker from any company is able to teach the robot to carry out a job by moving the robot’s arms in the desired motion and having Baxter memorize them. It is capable to learn and memorize the movement and to repeat it by itself afterwards. Workers just have to train it during some minutes, without programming it; consequently few software engineers are needed in the workshop exclusive for this robot. All of this doesn’t mean that Baxter doesn’t need traditional programming, it uses a combination of two and for that reason programming by demonstration is not all and is not going to replace traditional programming. Programming by demonstration “allows anyone quickly and easily program the robot to perform manipulation tasks on a production line, like picking up an object over here and moving it over there” (Clivaz, 2014).

When a worker is in front of a robot, he communicates the algorithm of the desired action to the robot. In order to transfer it, he only has to communicate to the machine the actions that are needed in order to carry out the job. This, because computers operate by executing these algorithms on data, so somebody to order this execution is needed. After the communication, “the computer synthesizes a program equivalent to the user’s internal algorithm, but expressed in terms appropriate to digital machinery” (Clivaz, 2014). In this point the robot is able to carry out the action and complete the task in the production line.

The communication of the algorithm is possible thanks to the sensors in every joint of the robot arm. Coming back to Baxter, it was given a lot of sensors along the arm and the body (Figure 21). When the worker teaches the task to the robot, the sensors captures the information and gives it to the software of Baxter. The information is processed and then sent to the actuators located along the robot. Finally the robot does the task. (Calinon, 2009)

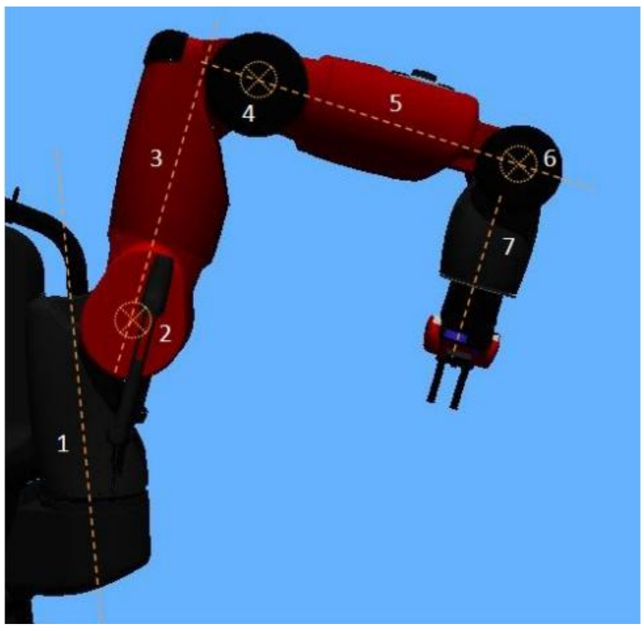


Figure 21. The seven joints of Baxter where are located the sensors and actuators.

It is important to know that this is a very new development and like many new developments, it has some problems that are being taken under consideration. In the following lines there are the three main problems (Nevill-Manning):

- “Programming by demonstration as incremental development; for the computer to be able to execute a task on behalf of the user, the user must be able to perform the task themself. Users may, however, have difficulty in expressing the precise algorithm that they follow”.

- “Abstract worlds create common ground for the expression of algorithms; Even if an algorithm for a task is completely developed in the user's mind, it will not generally be expressed in a useful form. In order to be useful, algorithms must be couched in terms of the computational hardware that is available to execute it".

- "Using actions avoids programming paradigms; Computer algorithms are usually expressed in terms of variables, loops and conditionals. These concepts may be unfamiliar or unintuitive to the computer user, so it is desirable to avoid them in communicating algorithms".

2.7 Adaptive system for the changing production flow

A general trend in industry is to reduce cost per produced part while at the same time increase the ability to produce on demand. This is related to a situation where the market in the near future can be expected to fluctuate more than today, and technological advances and fierce competition will bring forward new product designs as well as production methods. The result of this will lead to a need for production systems which in an efficient way can meet demands related to frequent product changes and low volumes, which in turn will require robotic systems which are flexible and easy to reconfigure (Kartoun, 2007). In the proposal, an organization to achieve this goal is shown. (Makris, Michalos, Eytan, & Chryssolouris, 2012). The aim of the paradigm is "achieving cost-effective and rapid system changes, as needed and when needed, by incorporating principles of modularity, integrability, flexibility, scalability, convertibility, and diagnosability" (Makris, Michalos, Eytan, & Chryssolouris, 2012). In the following lines, there is a presentation of the most important areas in order to increase autonomy.

2.7.1 Reconfigurable tools

Reconfigurability is defined as "the ability to repeatedly change and rearrange the components of a system in a cost-effective way" (Makris, Michalos, Eytan, & Chryssolouris, 2012). The aim is to support a smooth transition from today's mainly preconfigured and preprogrammed robot systems into adaptable and changeable systems. One of the points is to have a large variety of tools for the robots in order to provide them several options. With the help of these tools, the system becomes more autonomous and capable to face the production changes.

2.7.2 Intelligent Control and Monitoring

The second element consists in finding a good control and monitoring module, using a sensor driven approach to allow a non-centralized control framework. This intelligent control allows the reconfigurability of the changing production, thanks to distributed and open controls connected with the information from the sensors.

In the following lines there is a presentation of two control architectures that are most used in nowadays collaborative robots; SLAM and DAMN.

2.7.2.1 SLAM

Simultaneous localization and mapping (SLAM) is the "computational problem of constructing or updating a map of an unknown environment while simultaneously keeping track of an agent's location within it" (Bailey & Durrant-Whyte, 2006).

Many SLAM systems can be viewed as combinations of choices from each of mainly three aspects (Wikipedia):

- Mapping: "Topological maps are a method of environment representation which capture the connectivity of the environment rather than creating a geometrically accurate map"

- Sensing: "SLAM will always use several different types of sensors, and the powers and limits of various sensor types have been a major driver of new algorithms. Statistical independence is the mandatory requirement to cope with metric bias and with noise in measures".

- Kinematic modeling: "The $P(x_t|x_{t-1})$ represents the kinematics of the model, which usually include information about action commands given to a robot. As a part of the model, the kinematics of the robot is included, to improve estimates of sensing under conditions of inherent and ambient noise".

2.7.2.2 DAMN

The Distributed architecture for mobile navigation (DAMN) consists of a collection of independently operating behaviors and an arbiter. The arbiter generates a set of feasible action possibilities for the robot over a short time horizon, and the behaviors vote on these candidate actions. Votes may be weighed by a mode manager (Rosenblatt). The Pareto optimal action is then sent to the vehicle controller. In other words, DAMN consists of "safety behaviors which limit turn and speed to avoid vehicle tip-over or wheel slippage, obstacle avoidance behaviors to prevent collisions, as well as various auxiliary behaviors" (Rosenblatt). Figure 22 shows the organization of the DAMN architecture where several behaviors are sending votes in the arbiter direction. Then all these votes are mixed and finally the result command is sent to the vehicle controller.

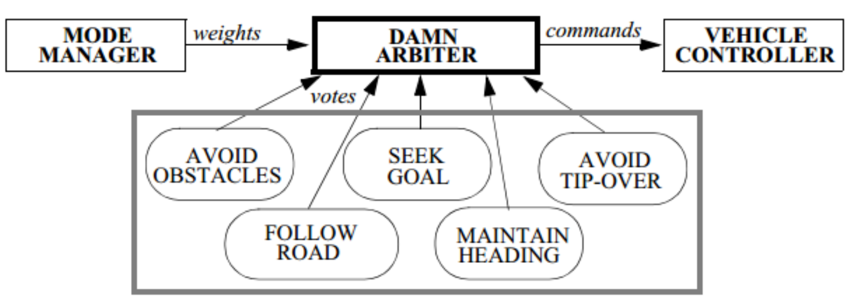


Figure 22. The Overall structure of DAMN.

Apart from these two control architectures, there are many more like NASREM, which is architecture from NASA or SAS and MMC. With the help of all of them, the workers are able to develop their software and hardware framework to control the robot in the workshop and help them to carry out the tasks in the assembly line.

2.7.3 Integration and communication architecture

With the help of service oriented and ontology technologies, the transparent integration and networking of the control systems (Staab, Walter, Gröner, & Parreiras)is possible. This kind of technology is considered one of the best, so in order to understand how it works, in the following lines there is an explanation about this kind of communication between robot and the worker.

In the field of science, ontology is defined as "a formal naming and definition of the types, properties, and interrelationships of the entities that really or fundamentally exist for a particular domain of discourse" (Staab, Walter, Gröner, & Parreiras). In the case of the collaborative robots we are talking about the human and the robot. With the semantic extraction it's possible to achieve a representation of the knowledge in order to improve the exchange of the information between the said elements.

To sum up, with the help of the oriented and ontology technologies, it's possible to achieve a really good interaction between the human and the robot and consequently facilitate a better adaption to face the changing flow production in the workshop.

3 Conclusion

To conclude, it can be affirmed that the main distinction between classical and collaborative robots is found in the interaction between the human and the robot. In the case of classical robots, this interaction is negligible and the communication takes place in an indirect way. However, in collaborative robots the interaction becomes a collaboration of both in order to achieve common goals. This leads to the two main characteristics of collaborative robots; safety and easy programming. The achievement of a completely safe robot allows both parts to share the workspace in order to reach a fluid and effective communication. The discovery of a new kind of programming by teaching the movements to the robot, allows the worker to adapt quickly in a changing production flow. Nonetheless, the industry is becoming more variable and competitive and as a consequence, the companies need to evolve in order to face it. In the thesis, a solution to this problem is presented. Firstly there is a workspace distribution with four cases in accordance with the localization of the human in relation to the robot. As a result of it, the system distinguishes four function modes. Depending on the kind of the task to carry out, the system will take different productivity levels to face the job in the co-worker scenario and change them quickly whenever the worker needs it.

Finally a robot paradigm is exposed not only to face the production changes, but also to reduce cost per produced part. In order to achieve a good result the paradigm proposes three main points that the collaborative robots system has to meet; Ability to repeatedly change and rearrange the tools of the system, a good control and monitoring module using sensor driven approach and a good communication architecture based on ontology technologies. With the help of the mentioned workspace distribution and the paradigm, every system is able to improve in order to face new changes and become more competitive in the industrial market.

Despite the fact that collaborative robots are gaining importance in manufacturing they are not replacing classical robots. Both are complementary and both are needed in most of the companies. However, it is proven that there is an important difference between having or not collaborative robots in the workshop. First of all, it's a way to lower the workload for the worker. Secondly, it leads to an improvement in the precision skills and consequently an accurate final result. Last, it allows reducing costs and increasing productivity at the same time.

Regarding the type of collaborative robots, after an accurate study it's considered that in general the best robot systems are based in three elements. First of all, a system based on two arm robots because they are able to handle more payloads, achieve a better accuracy and are more comfortable. Secondly, systems with mobile platforms that allow the robot to move freely along the workshop. Finally, with a friendly user interface that make the programming task easier for the worker in every different job. That being said, as a general case nowadays *Baxter* could be the best robot in the collaborative market, taking into account that it always depends on the kind of industry the robot is going to work.

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