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PRINCIPLES OF CONTROLS, SENSORIC AND SOFTWARE DEVELOPMENT OF AUTOMATION AND ROBOTS[2][3]

The automation and robotics are two disciplines in Industry without clear borders in between. Automation is strong related to the Factory Automation in Industry. Robotics is part of the Factory automation, but robotics is also represented in other fields like military, medicine or in the consumer section. Development in industry, medicine and consumer section is driven from technical and economic aspects. Decisions for development projects are mostly decisions direct related to the financial payoff or the market strategies. Many basic developments for robotics have had their roots in military. Development decisions in military projects, dependents more on the military benefit and on the technical feasibilities. This article will give survey of the relation from controls-, sensoric- and software development in automation and robotics. It illustrate the influence of technical market tends on technical developments.

AZ AUTOMATIZÁLÁS ÉS A ROBOTFEJLESZTÉS SZABÁLYOZÁSI-, SZENZOR-, ÉS SZOFTVERFEJLESZTÉSI ELVEI

Az automatizálás és a robotika az ipar olyan két területe, amelyek között nincs éles határ. Az automatizálás az iparban a gyártásautomatizálást jelenti. A robotika szintén az ipari automatizálás része, de számos más területen is alkalmazzák (pl. katonai, orvostudományi-, fogyasztói stb.). A robotika polgári alkalmazását műszaki-, és gazdasági okok motiválják: a fejlesztések közvetlen kapcsolatban állnak a piaci stratégiákkal, vagy a gazdaságossággal. Számos robotikai fejlesztés a katonai alkalmazási területen gyökerezik, ahol főleg a robot alkalmazások katonai előnyein van a hangsúly, és kevésbé a műszaki meglelőségen. A cikk a robotfejlesztéseket veszi górcső alá a szabályozás-, a szenzorika-, valamint a szoftverfejlesztés oldaláról. A cikk bemutatja a műszaki piac műszaki fejlesztésekre gyakorolt hatását.

I. LITERATURE REVIEW

In the technical literature there are many papers about Controls, Sensoric and Software Development. The most of these Books are scientific works, dealing with technical details and basic developments like SNYDER [1] and ZIVANOVIC [2], when they focused on the description of control theories of automation and robots.

SPUR [3] focused in his publication more on the description of the first controller architecture, programming and data exchange. In his thesis, gives the further development of control processes in production, the future trend of automation machines. In “Introduction to Robotics - Mechanics and Control” describes CRAIG [4] the relationship of control theory, kinematics and Software. These authors focus on the description of long term theories.

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Literature, for Principles of Controls, Sensoric and Software Development of automation and robots with an actual relevance, is more often found in technical and scientific magazines and journals.

In the VDI-NACHRICHTEN [5] April 1999 are presented KUKA´s PC based Robot controller as one of the first controller type with this design. The magazine AUTOMATION [6] 1/2012 focused in there article on the size and design of modern robot controllers and introduces the newest robot controller from DENSO, with a size of a sheet of paper.

VDI-NACHRICHTEN [7] 5/2010 and VDI-NACHRICHTEN [8] 9/2011 worked on the topic lightweight technology and introduces robot solutions with composite materials to reduces weight an increases speed and acceleration. They also discuss the impact from lightweight design and energy efficiency. The use of composite materials on robots with high payload is described in MASCHINENMARKT [9] 9/2006 with the introduction of KUKAs first palletizing robot with carbon arm.

Starting in 9/2006 was it the magazine MASCHINENMARKT [10] who starts to comment the competition for the crown of the heavy-weight champion, in payload, for robotics. At this time the challenge was between 400 and 500kg payload. In May 2007 the news magazine DER SPIEGEL [11] reported about the first robot with 1000kg payload. The follow up came in MASCHINENMARKT [12] 4/2009 with their first estimations above one tone payload.

HESSE [13] documented the history of sensor communication, using the thesis from RUOKANGAS [14], on the basis of an example with a ultrasonic sensor.

The automation-portal ELEKTROTECHNIK [15] described the fieldbus-communication of robots and sensors via Profinet and EtherNet/IP. It is obvious that fieldbus communication will enable the use of many sensor systems without the bottleneck in interface capacities.

On modern sensor development focuses several technical journals. VDI-NACHRICHTEN [16] 4/2000 described assembling robots with force-sensors. VDI- NACHRICHTEN [17] 5/2008 reported on sensor- systems which work as eyes, ears and nose for industrial robots.

In VDI-NACHRICHTEN [18] 10/2011 the journalist H. Weiss, reports in from the IROS-Conference in San Francisco and describes the trend to open-source software in robotics which accelerates the development speed for applications.

The topic safe-robots is found since 2003 in many technical literature. VDI-NACHRICHTEN [19] 5/2003 reports in from Japanese productions where they have a human-robot-interaction. The complexity of this subject is very close related to the national laws for machinery safety regulations.

On a lower safety level is the interaction robot- robot what is named as multi-robot or multi-arm systems. Here is the problem not so much the safety-law, than the technical solution. ZIVANOVIC [2] focused with his book “Multi-Arm Cooperating Robots: Dynamics and Control“ to this items. Since the dramatic grows of the energy costs in the last years, many technical publications and articles deal with energy-efficiently of robots. The investment costs, in relation to energy efficiently, are published in the magazine PRODUKTION [20] No.19/2009.

II. INTRODUCTION

The basic principles of automation and robotics have not much changed in the last 50 years when the first robots became developed. The mathematic background is even much older.

In the early years, between 1950 and 1985, the enhancement of controls was the moving power for the evolution in automation and robotics. The big technological steps in the electronic industry enable the manufacturer of automation equipment to come in leading position in engineering.

The controller, as the "brain" of the system, has had a key function for further development. Powerful controls are the precondition for powerful motors, intelligent sensors and fast software features.

The success of sensor systems starts later. Most sensor systems need fast and high capacity controls for their calculation power. Sensors are the interface to the environment and responsible for many feedback information's to the automation system or to the robot.

Touch-sensors, force-sensors, vision-sensors or much kind of measuring-sensors enables the automation industry the growth in various directions. For the automation branch, the sensor development is one of the important door opener for new branches.

Is the controller the "brain" of a system, is the software the "brainpower" behind. With large controller capacities and controller speeds, the opportunities of software, becomes unlimited. Software is in automation and robotics the most important development section where the suppliers put the focus on.

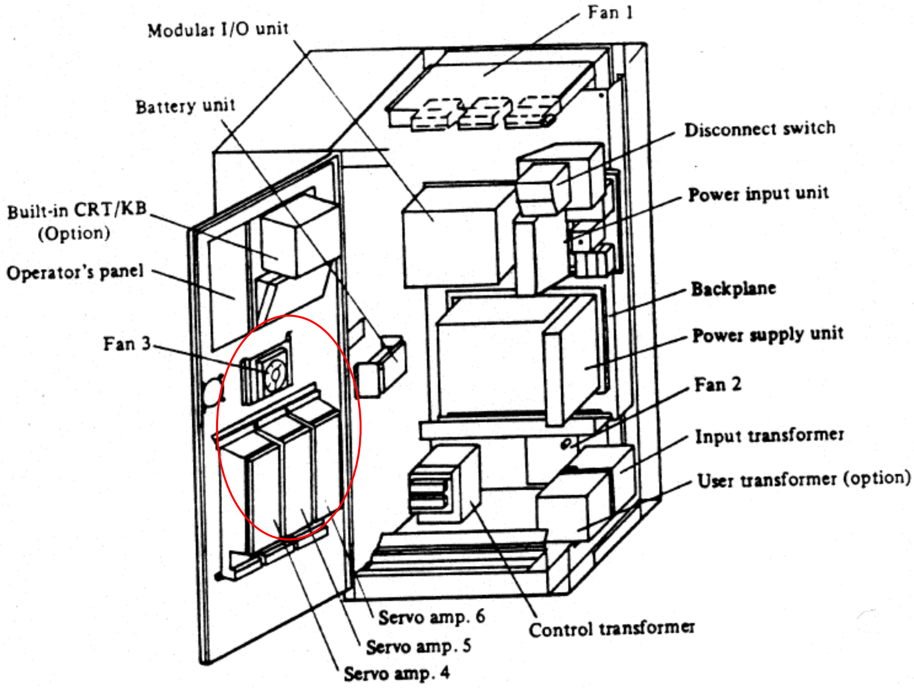
What for a gigantic tool software is, shows the success from Apple with their creation Apps where everybody can program software. With this idea, Apple opens up a resource from millions of software-developers for them.

With simulation-systems, offline-programming-systems and safety-networks, software solutions take place also outside of the robot controller.

III. DESIGN OF ROBOT CONTROLS

At the beginning of the 90s robot controls were very similar. After this period manufacturers soon began to develop individual principles of controls [5] [6] and implemented them into their robots.

However, the principles of power supply, main board, and servo-amplifier have remained almost the same for most producers. Fig. 1 shows one of the robot controls from the 90s [20]. It shows that because of the large size of the servo amplifiers' an additional controller- cabinet was necessary.



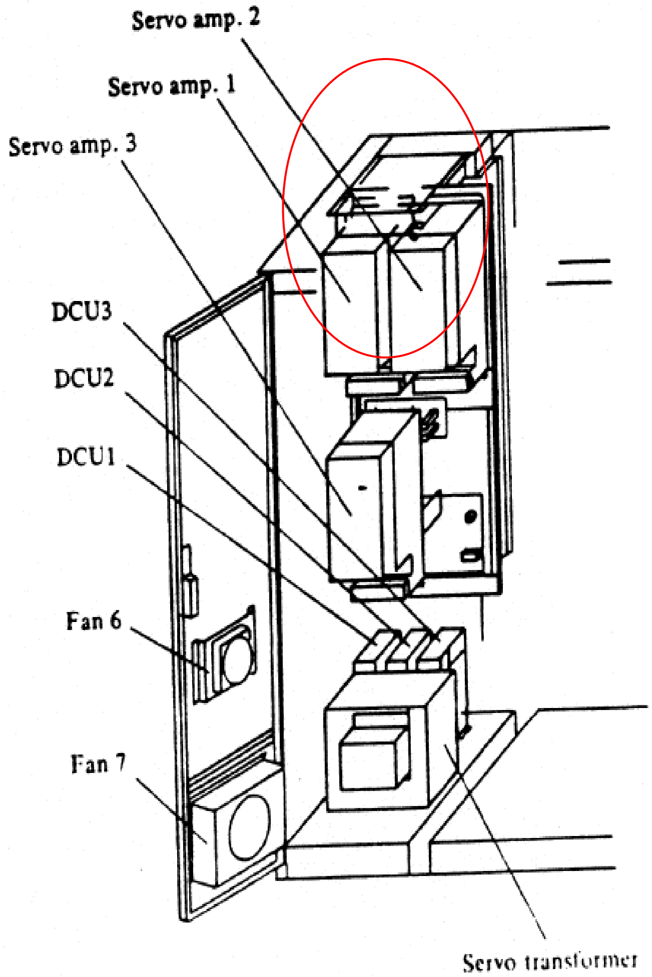


Fig. 1. FANUC S-420 Controller- Cabinet.
Source: FANUC Maintenance Handbook, S-420 Controller with Side-Cabinet, 1990

Fig. 2 shows a robot control from 2010. A 6-axis servo amplifier is implemented on one circuit board [21].

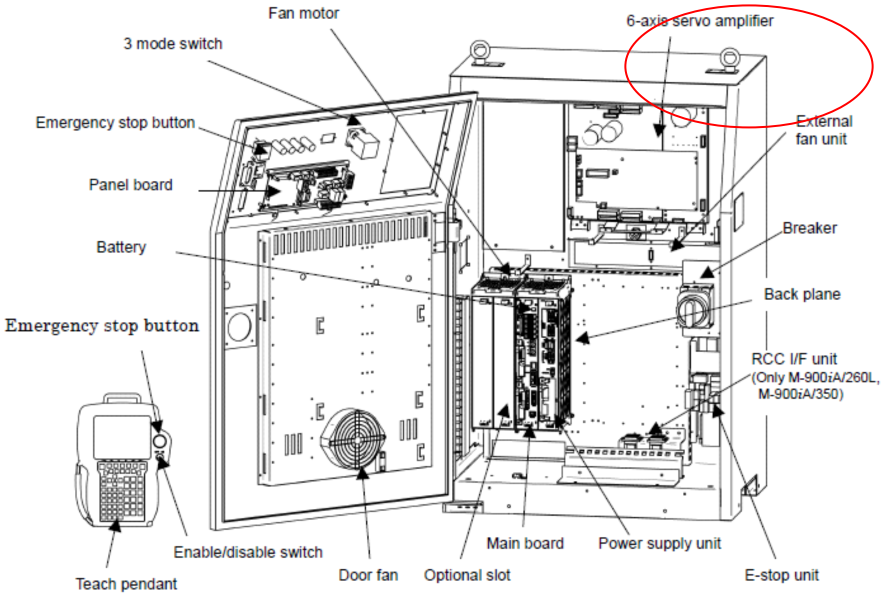


Fig. 2. FANUC R-30iA Controller
Source: FANUC Robotics Maintenance Handbook R-30iA, 2010

At this time engineers were not able to make estimations what equipment and performance future markets would require from robots and their controls. So there were different philosophies how to implement robots and controls into complex manufacturing processes. Producers of very specialized robots began at an early stage to manage several robot arms via one central control (Fig. 3 Schubert Robot). In such cases mutual linking plays a major role.

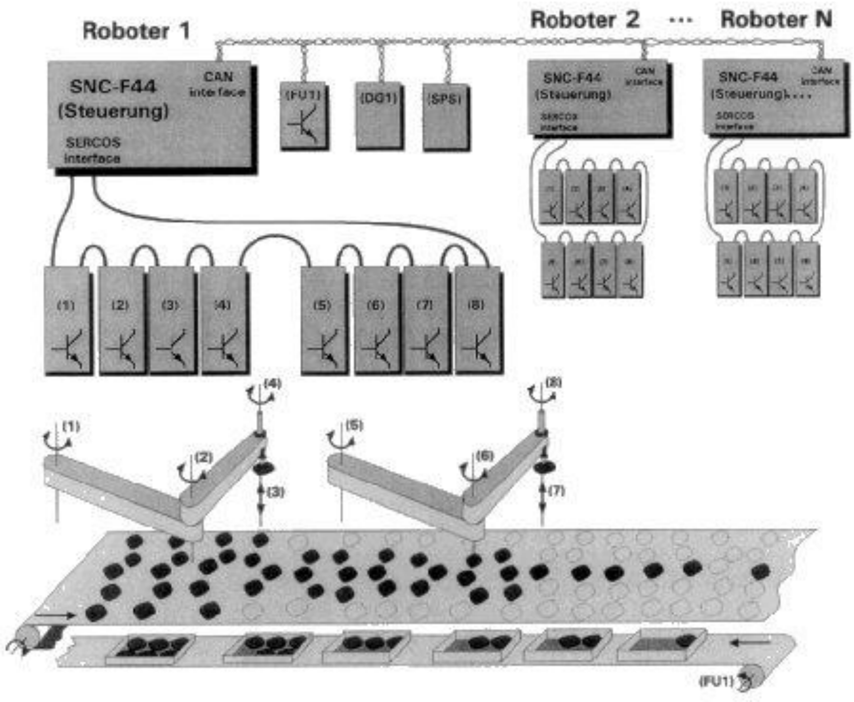


Fig. 3. Lachmann&Ring: Control scheme SCHUBERT Roboter.

Manufacturers of universal robots, namely the major producers of articulated and SCARA robots, concentrate on decentralized solutions. Communication between system control and robot control here works on IO-boards or BUS-systems.

Over the years many trends have taken over the lead and gained or loosed importance. However, the following aspects that influenced the last 20 years in robot development crystallized from this history:

1. Payload, speed and lightweight technology;
2. Sensors and communication with external sensors;
3. Software-Tools;
4. Safety robots systems or “safe robot”;
5. Multi-axis systems and cooperating robots;
6. Energy efficient robots.

3. 1 PAYLOAD, SPEED AND LIGHTWEIGHT TECHNOLOGY

First generation industrial robots in the mid-eighties had a load range of 10 and 90 kg. Those two values covered the major applications of robots. The 10 kg class was developed for arc-welding. 90 kg robots focused on mass application in spot-welding of vehicle parts in large car factories. From this both load types engineers developed further robot classes.

Comparing load types of 2001 (13,316 robots p.a.) with 2008 (18,137 robots p.a.) it is obvious (Fig. 4) that the share of robots with bigger loads has increased more than smaller robots with less than 5 kg. Accumulation in the 10 to 90 kg class has remained quite stable.

Comparison load types in % of articulated arm robots 2001 and 2008.

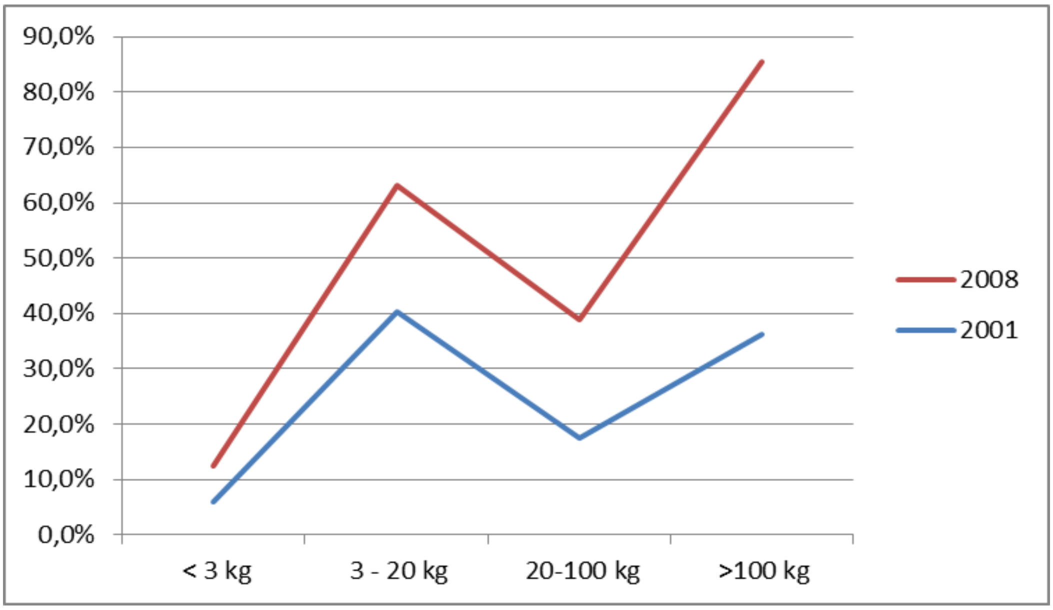


Fig. 4. Statistical distribution Robot payload types: 2001 to 2008, G.Mies, 2012
Source: VDMA Statistic 2001, Germany; VDMA Statistic 2008, Germany

One consequence of the growing application range of robots was an increased demand for higher load and speed. Processes got faster and the handled parts became heavier. In order to realize larger loads drives had to be equipped with larger power modules as well.

Moving masses and the resulting increased moments of inertia got problematic with a certain size; because robot drives have to change their moving direction with almost every movement of the robot arms. Because of this larger and faster robots are built with two drives per robot axis, which compensates this negative influence of higher acceleration torque. This doubles the number of power modules in robot controls. This resulted in more need for space and more need for heat removal. Larger controller-side-cabinets were the solution here.

3. 2 SENSORS AND COMMUNICATION WITH EXTERNAL SENSORS

The use of external sensors has been a continuously growing trend in robotics over years. Tactile sensors, electric sensors, optical sensors thermal sensors, and acoustic sensors – all of these systems were helpful to feed the robot with information from its environment. The costs for such systems at the beginnings of the 90s were, for instance, at about 150,000 DM for an optical sensor following the movement. This was 50 percent more than the costs for a robot.

Not only the costs limited the use of external sensors but also their capacity as well as CPU speed. Robots that had to change much data with sensors got slower in their movements. Thus manufacturers installed separate communication processors in the following robot generations.

Another hardware deficit was the limited number of interfaces in the robot control [14]. It was not before the introduction and acceptance of BUS systems and networks until the use of sensor systems got simplified. Manufacturers with PC based controls had clear advantages here, because most sensor systems were able to communicate with personal computers [5].

Robot producers with their own CNC based controls had to develop new communication software for each sensor type in order to enable the connection of external sensors. Because of this, many robot manufacturers started to develop their own sensors.

Today's robot controls have additional communication boards for processing data transfer to external sensors. Such independent boards ensure that no processor power gets lost and that speed performance remains stable.

The "seeing robot" is a synonym for the success of sensor technologies in robotics [17]. The market offers hundreds of different vision systems that enable the robot to perceive its environment – to see. Sensors are the interface between the digital world of simulation and offline programming systems and the real world in manufacturing.

3. 3 SOFTWARE-TOOLS

Software tools do not have any major effects on the architecture of robot controls. Only processor speed and memory space are directly related. This is one of the reasons for the rapid development of software tools.
Intelligent software is an easy way to increase a robot's performance without changing the hardware. For some manufacturers this software even works as a substitute for expensive external sensor systems. The "High Sensitive Collision Detection" (HSCD) is one example for such a solution.

The software monitors the drives' current permanently and detects possible collisions of the robot. Within milliseconds the software initiates countermeasures, which impedes damages on the robot and its periphery. Fig. 7 shows flowcharts of a robot, recognizing a collision with help of HSCD.

Fig. 5 shows a collision's effect on a robot arm <u>without</u> HSCD. The energy of the collision has to be resorbed by the robot mechanics. Damages in bearing, gear, grab and periphery are highly probable.

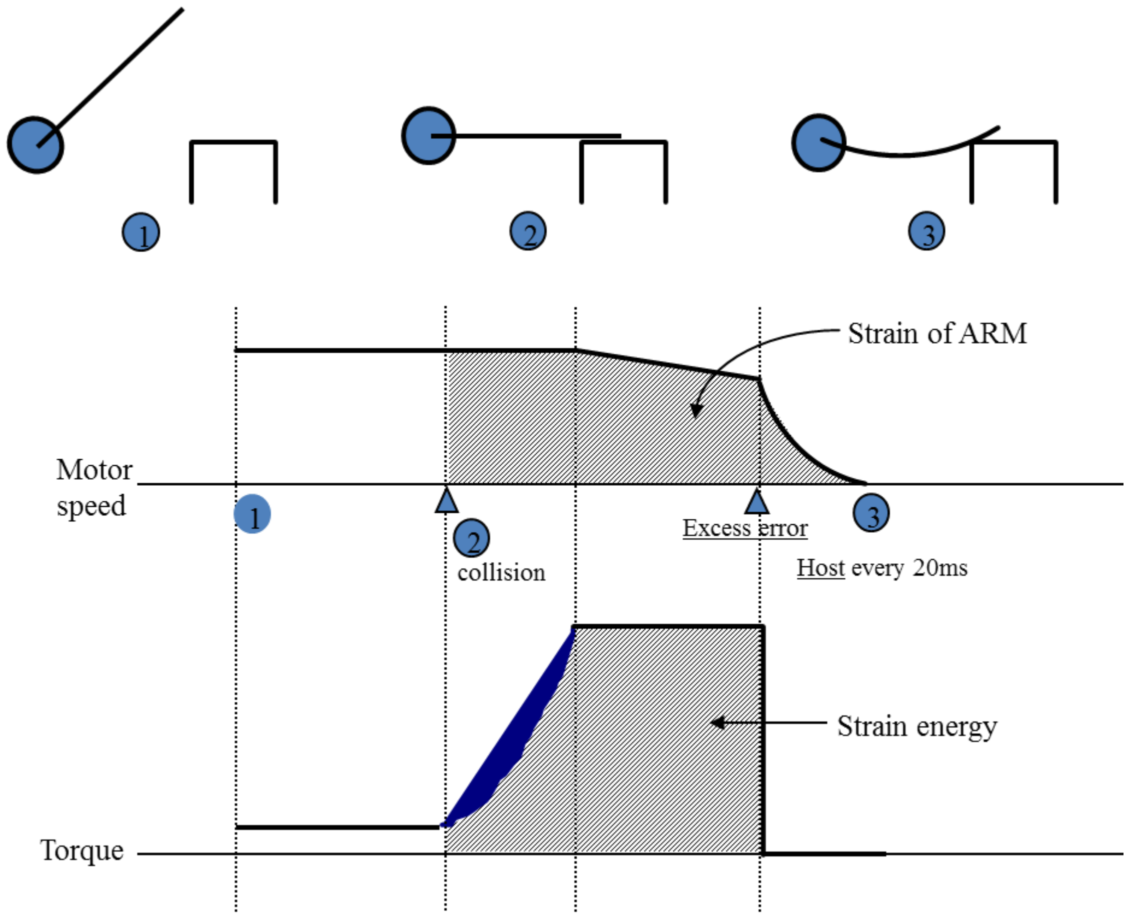


Fig. 5. shows the schematics of a robot arm <u>without</u> HSCD
Source: FANUC Robotics Deutschland, 2006.

Fig. 6 shows a collision's effect on a robot arm with HSCD.

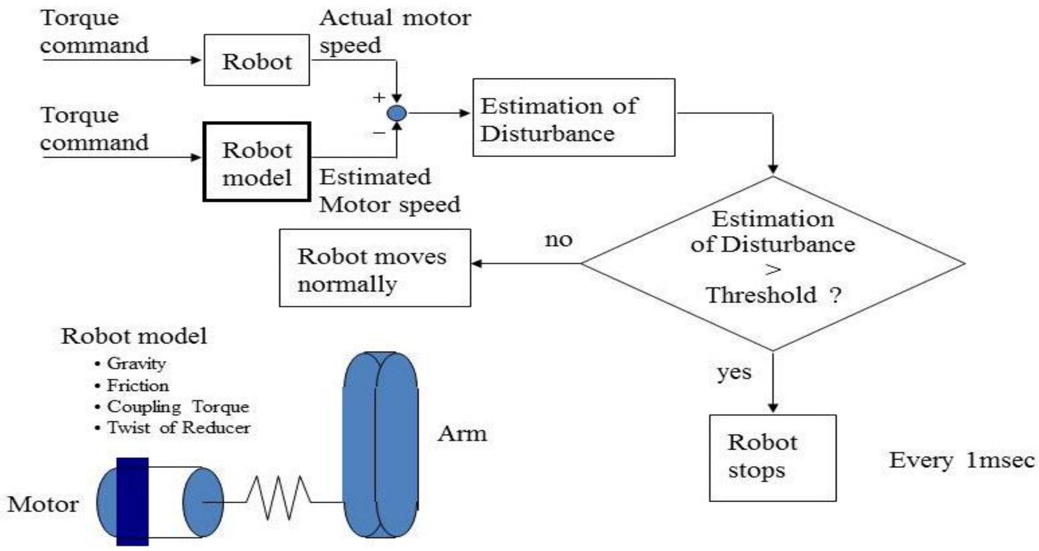


Fig. 6. Flowchart collision detection HSCD,
Source: FANUC Robotics Deutschland, Technical Presentations, 2006

In the moment of a collision the control recognizes an increase of moment and drive current Fig. 7. The affected drives will be changed with maximum torque to the opposite direction immediately. A great deal of the kinetic energy is resorbed by the drives which protects expensive grabs or parts of damages.

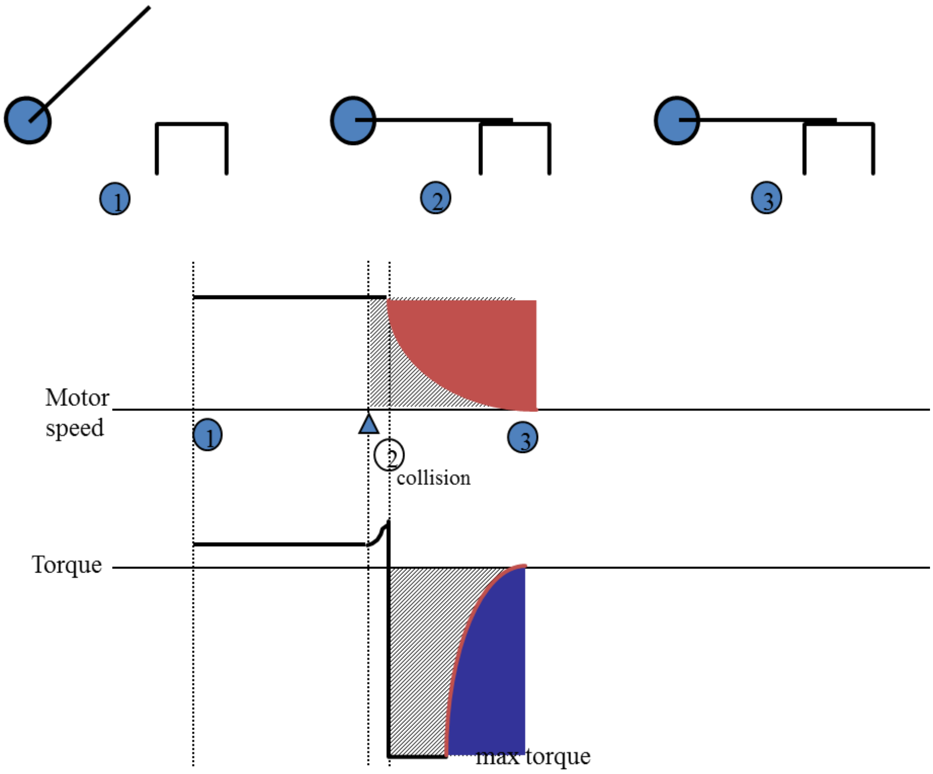


Fig. 7. shows the schematics of a robot arm with HSCD
Source: FANUC Robotics Deutschland, Technical Presentations, 2006

Software tools also make robots faster and more precise. Several manufacturers offer programs that optimize braking and acceleration curves of the different robot axes, which allow faster movements. Other programs consider production tolerances and improve the mathematic model of the robots kinematics. Thus, the robot is able to move on very precise paths. This feature is used mainly for robots in the field of remote laser welding.

The software tools are processed in the electronic components of the robot control. Memory, clock frequency, interfaces and BUS compatibility influence their performance.

3. 4 SAFETY ROBOTS SYSTEMS OR "SAFE ROBOT"

Robots of the security classes 3 and 4 are so-called "safe robots" that are allowed for operation in a common room with human workers [19]. This issue has been gaining importance since the robot density (number of robots) per manufacturing plant has increased more and more.

There still are processes that cannot be fulfilled by robots economically or technically. This leads to the situation that working areas have to be shared by robots and humans [19]. Most industrial countries allow such interactions between human workers and robots only under strict security standards. Respective installations have to be constructed in a two-channeled way. Operators of such robots have to secure each robot axis with two-channel cam rails.

On the one hand this measure is very expensive; on the other hand the robot kinematic is impeded by the large components (Fig. 8.)

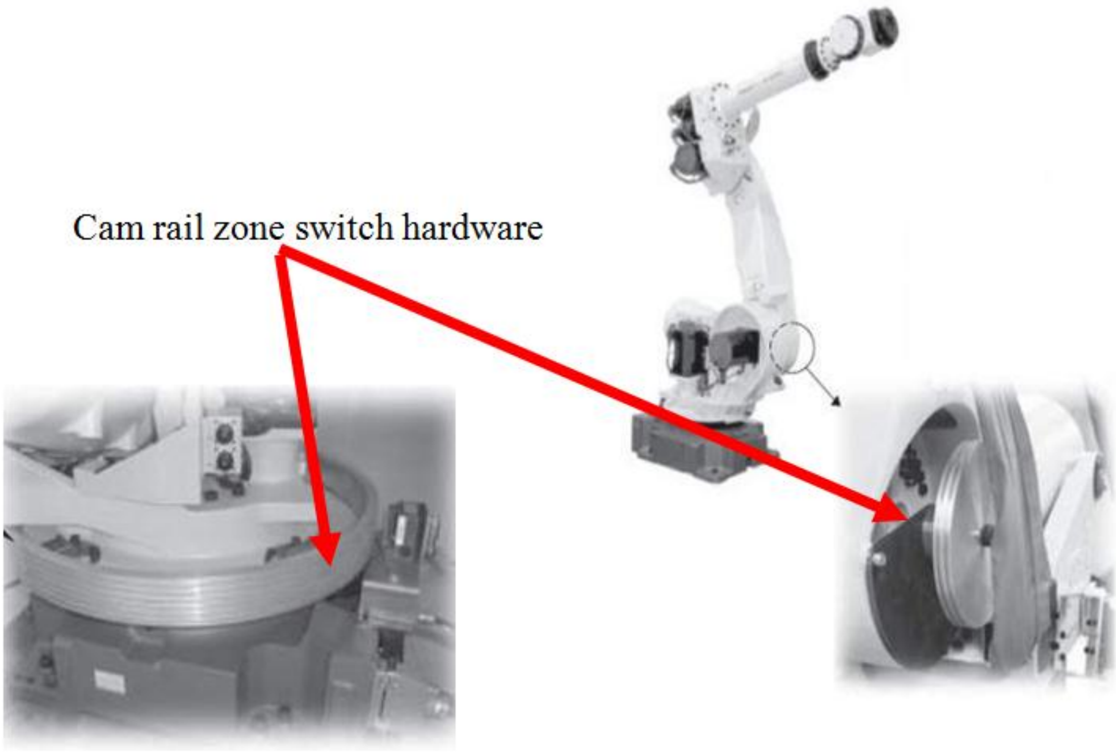


Fig. 8 shows axis 1 and 2 of a robot that are secured in a two-channeled hardware way
Source: FANUC Robotics, Technical Presentations 2006, Hardware zone switch

Modern robots are equipped with so-called dual check safety systems. It includes software as well as a hardware component and also ensures the required two channels.

Dual Check Safety (DCS) hardware uses redundant magnetic contactors, I/O-channels and CPUs. Mutual data and result checking are done by Main-CPU and Communication-CPU, very similar to the redundant systems in airplanes. Same external interface (E-Stop, fence, servo/MCC) are maintained as with the controller hardware based system Fig.9.

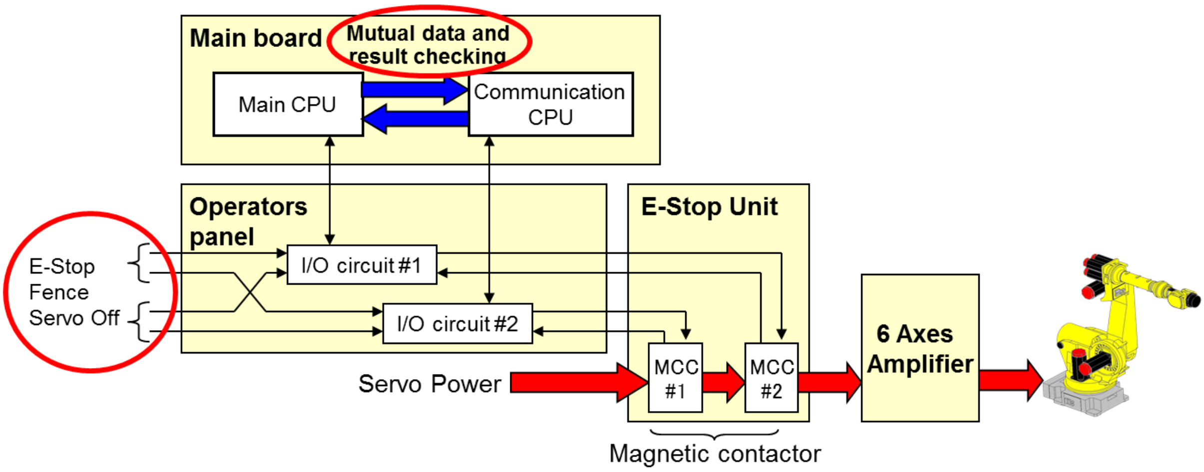


Fig. 9. shows the flowchart of the Dual-Check-Safety-system.
Source: FANUC Robotics, Technical Presentations, Dual-Check Safety, 2009

The robot position and speed can be safely monitored and the robot can be safely stopped to avoid hazards for operators and other persons Fig. 10.

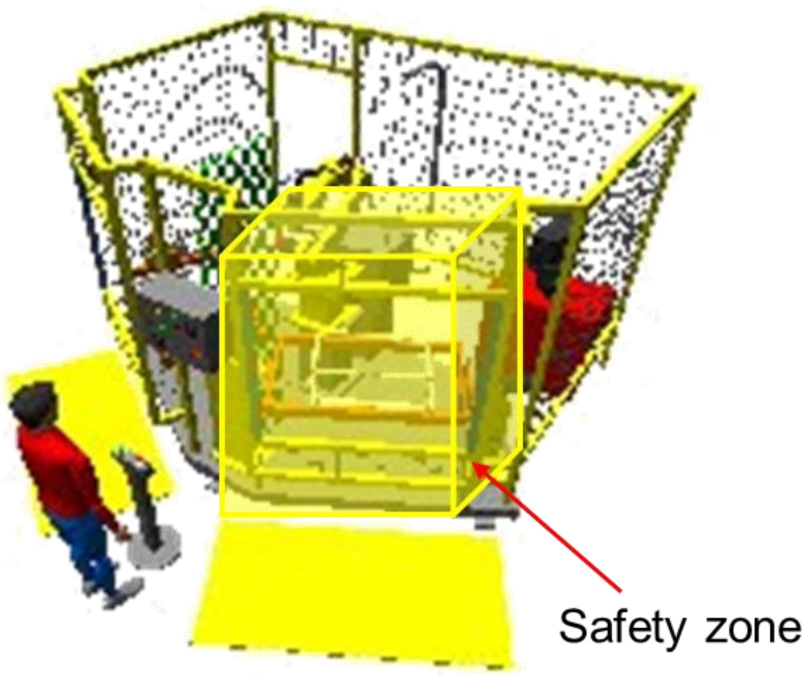


Fig. 10. Safety Zone
Source: FANUC Robotics, Technical Presentations, Safety Zone, 2009

Multi axis systems have been reduced to 16 axes for a long time. This means that robots with 6 robot axes and 10 external axes were sufficient to realize most industrial applications [2].

External axes are servo drives of positioning systems, grabs, or tools. They, too, are real robot axes that are able to move coordinately relatively to the tool center point (TCP). Again, manufacturers had different solutions to connect several robot arms.

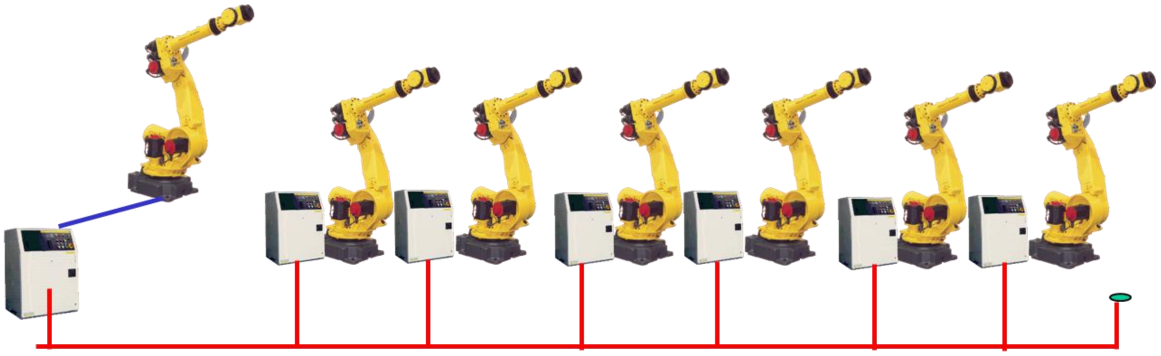


Fig. 11. FANUC Robot-Link
Source: FANUC Robotics, Technical Presentations, Robot-Link, 2002

In 2002 the first robot producers presented multi-arm-systems on the trade fairs. These systems connected multiple robots via Ethernet. Emergency stop circles also were connected, which enabled the robots to use a common work space. If one robot stopped for some reason the other stopped, too.

Thus, there was no danger of collision of the machines. Because of the option to use a common tool center point (TCP) there was also the possibility to program more than one robot in a single work space.

The overall advantage of multi-arm-systems was that a given space could be set up with more robots, which has reduced production time per manufacturing unit and the costs for work space.

As in the beginnings it was arc welding again that led to further developments, because it was not possible anymore to solve projects with only 16 axes. In particular tier 1- suppliers in the automotive sectors had to develop robot welding systems with shorter cycle times. In the new welding units up to 40 controlled robot axes were necessary. For the first time they used multi-arm-robots of which one single control had to manage four robot arms and up to four positioning systems. These axes had to be coordinated perfectly in order to achieve the required quality in the welded work pieces.

Connecting robots via Ethernet is a capable solution for handling and spot welding tasks. If, however, coordinated movements without time gaps are required, Ethernet connections are inappropriate because of their slow transmission rate of the signals (Communication delay of 4 robots control by Robot Link: 24msec). Arc welding is a good example for this. Today's requirements in welding quality have the consequence that robots and positioning systems have to move simultaneously and in a coordinated way. These technical requirements can only be fulfilled by multi-arm-robots who manage their whole movement with one CPU.

Complex welding units as they are often used by automotive suppliers can have up to 40 servo axes. The robot control, consequently, has to address these 40 axes without any time delay. The controls are organized in a way that there is one main CPU and four additional side controller-cabinets in which the power modules of the axes are installed.

For several years arc welding was the only application that required multi-arm-robot-systems with more than 16 axes. This situation changed when robotics found their way into the picking market.

Picking is the handling of mass production work pieces that leave the machines in huge numbers on conveyor belts and have to be sorted, arranged or packed by robots. Robot arms stand beside or hang above these conveyor belts and have the task to manipulate the products in a given way at very fast speed. Working areas of the single robots overlap and there is the necessity that the work pieces have to be assigned to certain robot arms. These circumstances are the reason for using multi-arm-technology in this field of application.

Multiple Robots Control by One Controller

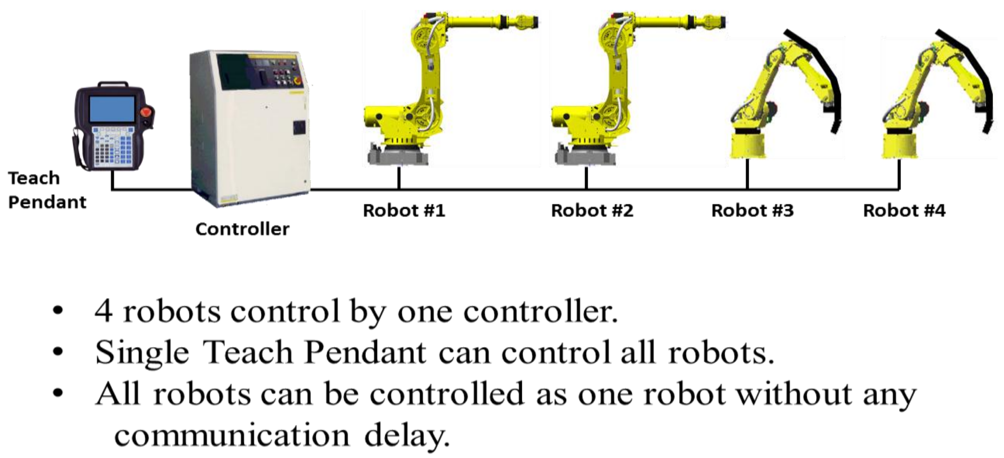


Fig. 12. FANUC Robotics, 2006, Multi-Arm Robots.

Such system requires only one controller and one Teach-Pendant. Servo drives of the axes have to install in a side controller-cabinet.

Theoretically, multi-arm-systems can be programmed with the Teach-Pendant. However, because of their complexity the programs are created offline with computers that simulate the robot system. Today the Teach Pendant is used for fine tuning only.

3. 6 ENERGY EFFICIENT ROBOTS

In the automotive industry the use of robots has increased disproportionately over the last decade. This development has been accelerated by the demands for cost efficiency and quality requirements. Car producers build the same models on different continents, namely in the regions where the cars are sold. Production methods and quality standards, however, have to be the same on each continent.

In the past producing a new car model required 500 to 1,000 robots for one project – depending on the production quantities of cars. Spot welding at the car body was the main application.

Today several car-types produced on one production line and the manufacturers have global production strategies. This led to the situation that robot applications are much more wide-spread today. Spot welding is still the most common task, but robots are as well used for transport, assembling, measuring, painting, loading and much more duties. In such projects up to 5,000 robots are needed.

Consequently, larger Car plants can reach robot populations of several 10,000 machines. These numbers are responsible for an increase in energy consumption, which makes this aspect an important cost factor [20].

Basically, energy consumption of robots is influenced by the number and use of their drives. This depends on the size of moved work pieces as well as their acceleration. Technical considerations like the size of drives and amplifiers or intelligent stand-by features are secondary. Thus, the operator has the biggest influence on the robots energy consumption.

Choosing the right robots related primarily to the load the machine has to carry. A correctly dimensioned robot is the basis for its efficient use. Even more important for an acceptable consumption of energy is the way how robot movements are programmed.

Every car driver knows that too much acceleration and intense breaking between two traffic lights leads to an increased mileage. Programming robots works in a similar way. The stronger the machine has to work against physical mass inertia; the higher will be its energy consumption.

Robot manufacturers react to these requirements by technical optimizations in mechanics, drives and amplifiers, electronics, and software. Lightweight construction is one of the keywords for this machine generation [7] [8].

Smaller and lighter robots not only reduce energy consumption, but also higher process speeds as well as reduced space requirements. Controls are equipped with smaller amplifiers that have less current drain and do not need the same cooling as larger amplifiers. Braking energy is recuperation and can be used again by the network.

The Energy-Flow-Analysis in Fig. 13 from K. Wagner, shows how large the part of energy demand only for the robot motion is. The basic of this analysis is the robot model FANUC R2000- series, payload 165-250Kg. This is worldwide the most used robot-class. 73,1% of the whole electrical energy is used for the robot-drives-units. This percentage distribution indicates very clear the optimization potential.

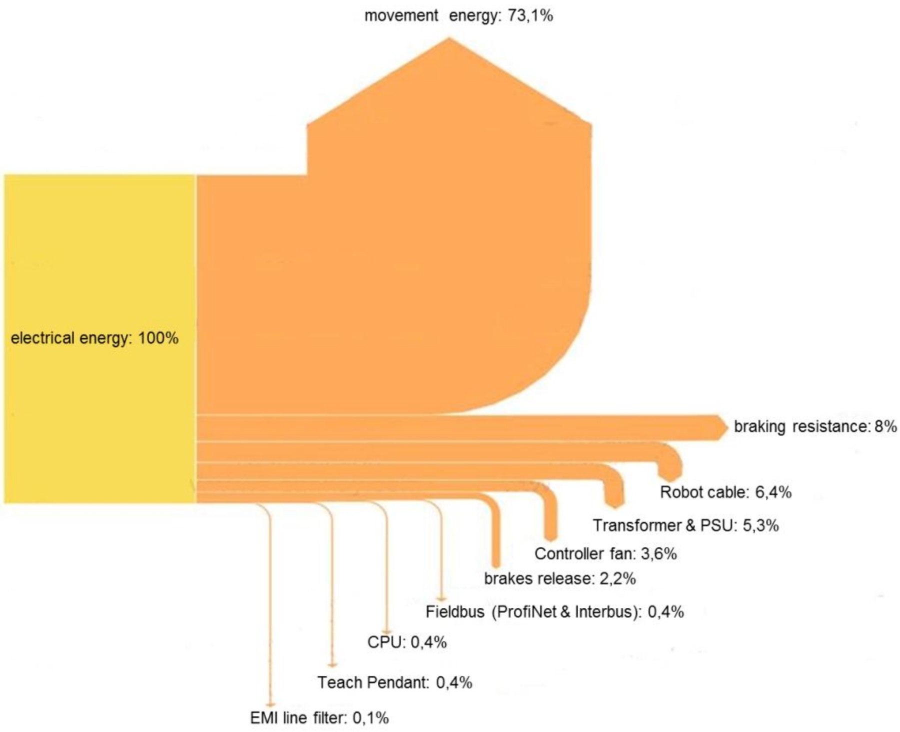


Fig. 13. Wagner, Klaus; 2011; Fanuc Robotics; *Energy flow analysis, Robot R2000 series.*

The biggest potential of energy consumption, the robot's kinetic energy, is dealt with by developing innovative offline programming and simulation software. These software tools are able to improve existing robot programs under consideration of energy aspects by having the robot's kinetic energy as close to the constant level as possible..

This method helps optimizing energy consumption for existing robot systems as well as systems that yet have to be programmed. How powerful this simulation-software is, shows an analysis of an optimizing-loop on a ROBOGUIDE station Fig. 13.

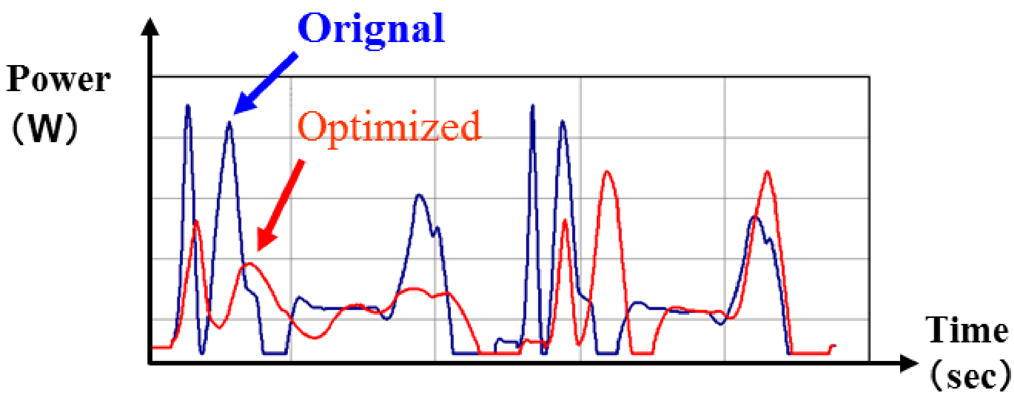


Fig. 14 Wagner, Klaus; 2011; Fanuc Robotics; *Energy-Optimizing with ROBOGUIDE*

Motion-optimizing reduces the energy consumption by 8,3 % versus the original motion-program. Cycle time remains unchanged.

IV. CONCLUSIONS

If you had to name a megatrend that has influenced the development of robot technology the last two decades and will keep influencing it in the future, it clearly has to be the issue of software tools. As mentioned in the introduction computer producer APPLE and their easy programmable APPS have shown that the world of software is as eternal as for instance the literary world.

Every programmer is able to create something completely new and to extend the features of computers, smartphones, and machines. If status quo of computer hardware stayed like it is today and developments were restricted to software, most people would not notice a slowdown of the overall development. Software unites competences and experiences of robot users and developers. To build the infrastructure for software developers is possible at any place of the world [18].

Even today software is a decisive factor in technological advancements. It calculates and compensates the deflection of robot arms under heavy loads and at high speeds software eliminates vibrations and resonance.

Also the communication management is controlled by software as robot security is almost completely based on software models that monitor virtual safety rooms and evaluates the situation by matching the redundancies of two processors. In the field of multi axis systems and cooperating robots, software is the foundation for common planning of movement paths. Beside CPU power on the hardware side this is an important technological part.

The advancements in energy efficiency of robots, too, are dominated by software tools. The development of economical drives and lighter materials is a long process that takes several years until noticeable results improve the efficiency. But intelligent software can optimize robot programs immediately and, thus, realize large energy saving potentials [Fig. 14].

The model of APPS has not reached the industry yet. Many industrial companies cannot imagine that software is open to third party users and those external programmers and software developers create programs without their own influence. The immense potential of development resources that already exists will enter the industry as well. Some robot manufactures have been working on this topic actively since 2010.

However, the unquestionably exposed status of software is not supposed to curtail the worth of controls and sensor systems. The simplified view that describes the control as the brain, the software as the intelligence, and the sensors as the senses of a robot, will help to evaluate the importance of each of the three factors. It is easy to recognize that robot control, sensor system and software are equally important.

The main differences between the three fields of technology are speed of development, necessary investment volumes, and potentials of resources. Controls will be developed at the pace that is valid for machine tools and computer technology. A separate development of robot controls cannot be expected.

The outlook for sensor systems is much more difficult. In particular the sector of vision sensors is connected to the developments in photography and camera technology. Speaking of consumer electronics advancements in these sectors are much faster than in the industry. Thus, advancements in sensor systems will not develop evenly. While vision sensors will take the speed of consumer electronics, touch sensors, force sensors, and measuring sensors will keep the momentary speed of its industrial environment.

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