CYBERNETICS APPLIED TO A SIX-LEGGED ROBOT

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ABSTRACT

Robots are used for so many different reasons such as industrial fabrication, medical assistance or military tasks. But what is it, that makes machines doing the right moves in order to accomplish a given task? And what is it, that makes them doing this autonomously and accurately timed? Essential for explaining this, is cybernetics. To understand the cybernetic principles, it is fundamental to be aware of the fact that it does not arise in robotics. It appears in many other areas such as economy, project management and even politics. From animals we can learn a lot about motion sequences for the development of walking robots, because of evolution animals are acting with a perfect coordination of their movements. On the long term the development of robots should lead to autonomous acting, because finally the independence from leading controlling processes makes the robot a real useful additive. The aim of this paper is to depict the requirements to robotic systems in order to enable cybernetic operations, which is finally indispensable for autonomous acting.

Keywords: cybernetics, robotics, hexapod, system learning

1. INTRODUCTION

The original idea of a robot was an autonomous operating machine, which was supposed to support humans in their everyday life. First models had very little abilities only for simple tasks. But with the amending technology the complexity of robots increased and they were able to accomplish more complex tasks in less time. But on the other hand, it became more difficult to control these robots. When a robots complexity achieves a certain range, it becomes extremely difficult for a human to control the robots processes just by his natural senses. So the next logical step has got to be to teach the machines controlling their movements and their tasks by their own.

A great support for achieving this is the science of cybernetics. It is a natural science, which describes the functioning of things in general. Cybernetics combines the basic theories information and communication as well as regulation and control. By regarding these major theories and by using the mechanisms of self-control, self-regulation and self-organization, cybernetics can serve to keep a process under control and even to make it viable (Malik 2013, Malik 2008).

In order to operate without the influence of humans, it is necessary for a robot to use sensor technology. The process of measuring data with a sensor and reacting to it in an appropriate way is described by cybernetics. So, the main purpose of this work is to view the huge field of robotics as an application area of cybernetics. It will be investigated, how big the impacts of cybernetics in robotics are and how much certain processes and structures in robotics make use of the cybernetic principles. This processes can include a robots basic movement patterns or even its visual appearance and kind of construction. In order to make cybernetic processes even better, bionics can be very helpful. Bionics describes the art of learning from nature. For example, the functional principle of an aircrafts wing is copied from a real animals wing.

Controlling the basic movements of robots is just one kind of a cybernetic process. But it is much more suitable when correct reactions to unexpected influences are needed. Imagine an obstacle appearing in front of a moving robot. In which direction is it supposed to go? And how can the decision be made before the robot crashes into the obstacle? That are the two most difficult aspects cybernetics has to deal with. The best solution to a problem has to be proceeded accurately timed. All the impacts, that could affect to the correct operating of a robot annoyingly, have to be detected. Unfortunately, there could be an infinite number of different kinds of influences. So theoretically, the implementation of a system, which is able to react to all different kinds of influences, is needed.

This work views a six-legged walking robot as research platform and investigates several concrete scenarios, which are likely to occur in the robots later operating environment. These scenarios will be verified concerning the effective usage of cybernetics. The aim of this should be to obtain useful insights about the requirements to a hexapod in order to work in a cybernetic and viable kind of way and not to get out of control with rising complexity.

The paper has the following structure: In section 2 the cybernetic principles are described with their main aspects. Section 3 depicts a brief state-of-the-art of a hexapod robot and what parts play a major role for enabling cybernetics. The fourth section describes the main elements a hexapod needs to enable cybernetics in general. Afterwards, in section 5 the cybernetic rules are discussed again regarding the hexapod with the help of a number of real-life scenarios. The needed actions to certain occurring influences will also be presented in this section. Finally, section 6 concludes these findings and declares the main requirements to a hexapod robot in order to be able to operate in a cybernetic kind of way.

2. CYBERNETIC PRINCIPLES

In order to apply cybernetics to the huge area of robotics and especially to a six-legged walking robot it is required to understand its basic working principles. First of all, it is necessary to declare why systems, which do not consider the cybernetic rules, can never be viable.

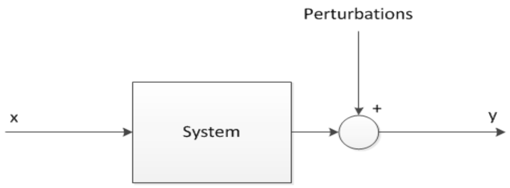

Figure 1: System with straight forward oriented Control

Figure 1 shows a model of a system with its input *x* and its output *y*. Possible perturbations are added to the systems output and distort it. This kind of systems are simple, but exactly this simplification unavoidably leads to the main problem cybernetics has to face. When the systems complexity rises, this kind of controlling becomes impossible because of the missing information if a desired target has been achieved or not. The input can not be adapted to the output dynamically if the outer perturbations to the system change.

2.1. Complexity

In fact, it is not the system itself that needs to be controlled, but rather its complexity. But when trying to control any kind of system like shown in figure 1, it is very important to differ from simple and complex systems (Malik 1998).

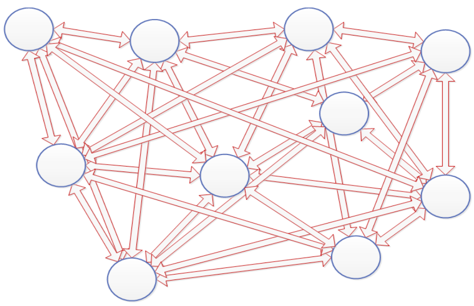

Figure 2: System with a high Complexity

When systems become more complex as shown in figure 2, it gets impossible to keep it under control or grasping it with our senses, because the degree of cross-linking between the elements is simply to high. In this way, the system becomes instable and this will lead to an undefined output. That means that a little change of the input can cause an enormous change of the output. Systems with networked connections and mostly acausal behavior do not appear in our everyday life very often, so we have a natural averseness to it. The complexity of a system rises with the increasing number of elements and also with the range of networking between its elements (Vester 1999). It is a matter of fact, that such complex systems with nearly no structure are not viable for very long. So from this point of view, it would be the best to keep a system simple and reduce its complexity as much as possible. But it is essential to clarify that this is not always the best way, because complexity means functionality, it makes a system powerful. The worst case when reducing a systems complexity would be to destroy some important or even its main functions.

It seems that this matter must inevitably lead to another strategies of organization. With the increasing number of elements and higher degree of cross-linking a structural transformation of these organization strategies needs to be done. In other words, it is possible to handle more complexity with a higher developed strategy of organization, or even more general, only complexity can cope with complexity (Vester 1999). This can be achieved by grouping several elements of a system to a subsystem and view it as self-organized. This brings the advantage that a major control process only have to manage the communication between the subsystems instead of all the single systems. Such a structural organization is shown in figure 3.

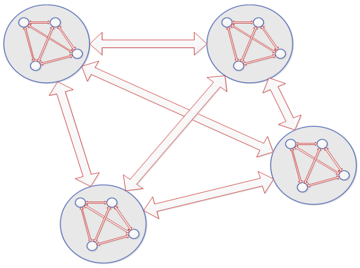

Figure 3: Organization of Organizations

2.2. Control with the Help of Cybernetics

As complexity is now known as the main problem cybernetics has to cope with, some core issues can be defined. How can you control a systems complexity? How can a system be controlled and regulated when it is complex? What characteristics does the systems structure need to have in order to cope with its complexity (Malik 1998)?

To answer these questions you have to make aware the three core values of nature:

- matter
- energy
- information

If you only consider the matter of a system and the energy you implement to it, a typical straight forward oriented control like in figure 1 is the result. If the perturbations suddenly change, the system would react differently to the given input, which can lead to an undesirable output. Consequently, you have to regulate the input information manually according to the influences to the system. But in order to do this efficiently, you have to know the systems characteristics in detail. You always have to know what output will have to be expected when the input data changes. This procedure could be very difficult under certain circumstances, especially when the influences change rapidly. It seems obviously that only considering matter and energy is too less for an efficient regulation.
So apparently the key value for success is information. In this context, information can also be seen as organization. In order to achieve the desired result, a so called feedback loop is built.

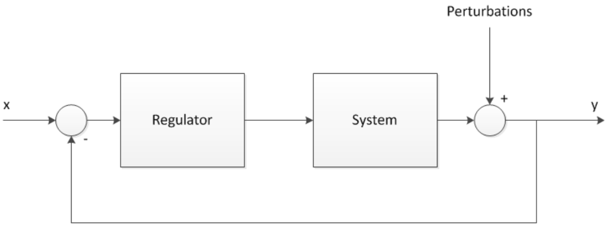

Figure 4: Basic Control Cycle

In figure 4 you can see a classic control cycle with this feedback loop. The actual output of the system is fed back to its input side. There it is compared to the input and the resulting difference, or the regulation deviation, is the input signal for the so called regulator. This unit has the task of calculating the new input for the system, according to this deviation. This process lasts until the wanted output is achieved, which means it must be equal to the input. Such a procedure is called adaptive readjustment and is the basic enhancement, which cybernetics brings. The main requirement for such control cycles is, that the result is achieved in finite time. Norbert Wiener, an American mathematician and founder of cybernetics expressed this matter as follows (Wiener 1961):

> ”When you desire a specific output to follow a given input pattern, the difference between this pattern and the actually performed output value is used as a new input to cause the part regulated to change in such a way as to bring its output value closer to that given by the input pattern.”

This exactly describes the big improvement, which organization in form of information should bring. The control cycle as in figure 4 describes the technical requirement of cybernetics to all cybernetic processes. With the help of the feedback loop it will be prevented that a systems gets out of control.

3. THE HEXAPOD WALKING ROBOT

A hexapod robot is a six-legged walking robot, which is supposed to imitate a real animal as much as possible. Its intents are to move in a fluent kind of way and react appropriately to unexpected situations. It should be able to recognize its environment and especially obstacles in order to move around them successfully. Another purpose of the hexapod is to receive an aim in the form of coordinates and then walk there autonomously and on the shortest path. There are many different implementations of such robots, but the main tasks are always the same.

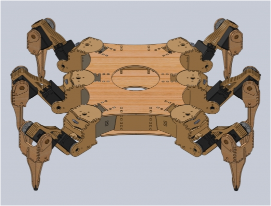

Figure 5: A possible Chassis of a Hexapod Robot

A concrete implementation of the University of Applied Sciences in Upper Austria is shown in figure 5. It is powered by 18 servo motors, three for each leg. That also results in three degrees of freedom for each leg. The chassis of the robot itself consists of ply wood. That is lightweight and stable simultaneously. The brain of the hexapod is a self developed hardware platform, which is called *Sandbox*. It combines a field-programmable gate array (FPGA) with a micro controller. On the FPGA the so-called *Robotics Chip* is implemented, which is responsible for generating the pulse-width modulation (PWM) signals, which serve as input for the servo motors. The micro controller takes care of the communication and the signal routing between the *Robotics Chip* and the servo motors. This implementation of a hexapod is our departments main platform for research in the field of mobile robotics. It is able to receive commands in terms of mathematical vectors, which are related to the hexapods local coordinate system. From these input vectors it calculates the direction, in which it should go. So, all the collected information and results in this paper base on this platform.

4. REQUIREMENTS TO THE HEXAPOD

There are certain parts and elements a robot needs, which are indispensable for enabling cybernetic processes. The availability and accuracy of these elements determine the reachable effectiveness and power of the desired cybernetic sequences.

4.1. Sensors and Actuators

Sensors and actuators might be the most important parts of a robot to allow the implementation of a cybernetic process.

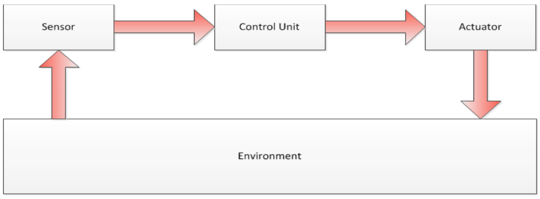

Figure 6: Structure of a simple Sensor Cycle

This technical appliances scilicet represent the beginning and the ending of a cybernetic control cycle as shown in figure 6. The needed data for the feedback mechanism is grasped with sensing elements and after passing through all the parts of the control cycle, the calculated controlling signals affect the actuating elements, which take the desired actions. To enable a completely autonomous operating machine in order to observe the environment as accurate as possible, a high number of such elements is needed.

4.2. Bionics

Similar to cybernetics, bionics is interdisciplinary and can therefore be applied to many different industries. In order to make use of bionics means learning from the construction, process and development principles of nature in order to cross-link humans, environment and technics in a positive kind of way (Nachtigall 2002).
So what can we learn from nature to develop a hexapod? The answer to this question is obvious - everything we need for the effective operating of the hexapod. Ranging from the basic movement pattern to get the ability of walking in general, to the best kinds of leg coordinations in order to get a fluent and energy saving locomotion. You can also copy the geometric structures of an insects corpus, its legs and especially the particular limbs to achieve the best results. It is essential to understand, why an insects leg is designed as it is. Once you have done this, you can try to rebuild it and apply all the gained knowledge.

5. CYBERNETICS AND THE HEXAPOD

As we already know that cybernetics can be applied to control complex systems like the hexapod and after depicting the main abilities a robot has to provide in order to enable cybernetics, we can now model a number of specific scenarios, which are typical for the hexapod, and analyze them regarding their cybernetic aspects. By simulating the behavior of the hexapod within these specific processes, the appearance of cybernetics will be investigated and the criteria to the hexapod in order to apply cybernetics successfully will be clarified. The processes we want to observe are as follows:

- basic locomotion
- changing environmental impacts
- overcoming of obstacles
- error handling
- system learning

These chosen processes are tasks, which are typical and crucial for a hexapod walking robot. Nevertheless, it is just a selection of some major operations and do therefore not describe the whole behavior of the hexapod.

5.1. Movements

With the help of bionics we can learn how the hexapod is supposed to walk in order to use its resources in the best kind of way. But what about the motion pattern itself? The different gaits just provide information about the deflection of the particular limbs and the order the legs are accessed. But this is not enough to achieve autonomy. It is too less just to tell a leg, that it has to move its tip to a fixed point in the coordinate system, because this would lead to a stiff looking movement without any information about the achievement of the desired position.
When you remember the classic control cycle in figure 4, the input for the control cycle in this case is the set of desired angles of the particular limbs. Thus, the limbs, which form the system of the control cycle, apply these angles and the feedback can be done with an angle measuring sensor or by calculating them with the help of inverse kinematics. As long as the desired angles are not achieved yet, a regulator has to calculate the ruling difference permanently and provide the according input to the legs engines. With all these parts the control cycle can be closed and a cybernetic process can be performed. When the control deviation of the control cycle is zero, the desired position is reached and the leg keeps this position until a new input is valid. A visualization of this case you can see in figure 7.

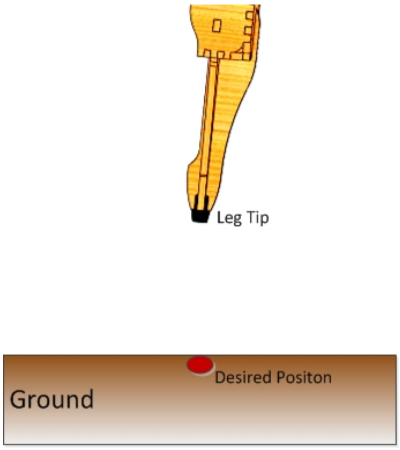

Figure 7: Basic Movement within a Control Cycle

One possible problem with this control cycle could now be, that the calculation of the particular angles with the help of inverse kinematics lasts longer than the interval, within the feedback data is sent to the comparator of the control cycle. Thus, it is the duty of the developer to choose the correct feedback interval in order to avoid this problem.

5.2. Changing environmental Influences

5.2.1. Acclivity

For an effective walking over all kinds of grounds it is required to adapt the kind of walking to the actual ruling ground conditions. To achieve this ability, the environment needs to be observed permanently.

To regard to the cybernetic control cycle from figure 4 again, an inclination sensor could serve as the feedback delivering item and give information about the actual tilt of the ground. When this tilt exceeds a certain limit value, the motion controlling algorithm should switch to another gait. But just switching to another gait does not form a control cycle.

Firstly, it is important to figure out, if ascending of descending acclivity has to be handled. This information you get from the inclination sensor. Then the required action would be to shift the hexapods weight into the direction, which is closer to the slope. This action should not only prevent from falling over, it also correlates with a basic cybernetic rule, which declares the usage of existing surrounding forces, which would be gravity in this case. When the haxapod should be pushed to the ground by the gravity, a balanced position is required. In order to achieve this, a new angle set for all the legs, which describes the desired position to keep the hexapod stable, is calculated according to the particular value of acclivity. This information is the input for the control cycle. The feedback data can be determined with the help of inverse kinematics again. When all the limbs angles are calculated, you can deduce the whole position of the hexapod from these angles. This calculated position is sent to the control cycles comparator and the control deviation defines the new input of the system, which are all the limbs in this case. When the required position is occupied, the hexapod has its new initial position, to which the actual gait has to be adapted now.

5.2.2. Ground Unevenness

It is not very innovative to assume that the hexapod will exclusively walk on even underground. Exactly this ability to walk through uneven terrain should be the big advantage of walking robots over wheel robots.

Imagine the situation, a stone lies exactly on that point, to which the leg tip is supposed to move according to the algorithm. Such a trivial scenario makes it clear, that even for the movement of one single leg already a cybernetic control cycle is needed.

First of all, the hexapod needs sensing elements, which are able to give information about the tip of a leg. This could be a force sensor in the leg tip, which tells the controlling unit, that the contact with the ground or another object is given, or a kind of visual sensor like a camera, which observes the legs.

The classic control cycle like in figure 4 is not really correct in this case, because here we have a so called interleaved control cycle. You can consider this as a control cycle within a control cycle and the inner cycle, which regulates the forward locomotion itself, forms the system of the outer cycle. When you now consider this outer control cycle, the earlier mentioned sensor gives feedback about the connection from the leg tip and any object. If an object lies between the leg tip and the desired position on the ground, or even a hole is at the position the leg tip is supposed to move to, the inner control cycle must be aborted or delayed accordingly. This means, that the outer control cycle must have a higher priority than the inner one, because it is wrong to move to the given coordinates obstinately, when it is not possible.

5.2.3. Aerodynamic Resistance

In order to cope with changings in aerodynamic resistance, a velocity sensor could be used to measure the wind force, because the velocity of the wind is proportional to its force. When the wind force increases now from a certain direction, the hexapod has to shift its weight into this direction and also move closer to the ground in order to counteract the wind. If the hexapod does not have the ability to react in that kind of way, the wind has a maximum contact surface and the hexapod could fall over in the worst case. The measured wind force is compared to the limit values, which have to be defined by the developer, and then the appropriate position of the hexapod is the input of the control cycle. Now the actual position needs to be observed in order to close the cybernetic loop. This can be done with the help of inverse kinematics again. The calculated position is the feedback data within the control cycle and when it is equal to the input position, the desired position is achieved. This target position has to be dependent from the wind power. It has to be found out experimentally in order to counteract the actual level of wind.

5.3. Obstacles

To achieve the ability of passing obstacles successfully, the hexapod generally needs the skill to recognize the obstacle. Possible sensing elements for this could be a distance sensor or a visual kind of sensor like a camera. Or the even better solution would be the accurate knowledge of the area before the hexapod starts acting. This would be possible with a cartographic recording of the area. Once the hexapod recognized the obstacle, it has to find out the best way around it, if there is anyone at all.

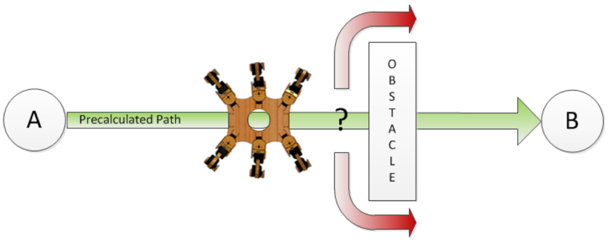

Figure 8: The Problem of choosing the correct Direction when an Obstacle appears

In figure 8 it does not matter, if the hexapod passes the obstacle on the left or the right side, because the distances are the same. Potential factors impacting such decisions could be the grounds actual inclination, the accessibility of both sides or even the luminance on each side. It is not very likely that the hexapod always reaches the obstacle exactly in its center, so another influence to this decision could be, that into one direction the distance to the obstacles edge is shorter than into the other. However this decision is made, once a direction is chosen, the actual controlling process begins and cybernetics comes into play.

The hexapods position represents the system controlled. The input of the control cycle are all points of the precalculated path from the position in front of the obstacle to point B. Now the hexapod is supposed to walk along the obstacles edge until it reaches the precalculated path again. In order to manage this, a distance sensor can be used to control the distance between the hexapod and the obstacles wall. Due to the set of inputs and the permanent comparison of them to the actual position, the adaptive readjustment is successful when one point out of this input vector is reached. If this is the case, the obstacle has been bypassed successfully. From this achieved point, which is nothing else than a position related to the inertial coordinate system, the hexapod continues its way on the precalculated path.

But what is the hexapod supposed to do, if the obstacles edge never leads back to the precalculated path? This situation could cause a big trouble and an appropriate error handling strategy needs to be accomplished.

5.4. Error Cases

Even the best controlling algorithms can cause errors. A perfectly autonomous operating hexapod would need to have an error handling procedure for as many problems as possible. The biggest problem of all is probably to recognize a problem as such. Within every control cycle and especially within their controlling algorithms there have to be defined several limit values in order to recognize problems. These limit values can have all different kinds, because every particular task has its own special limitations. Examples could be extreme values of distances, temperatures or even time. Basically, there must be defined one or more limit values for every quantity the robot can measure. Every set of limit values has to be matched to its particular controlling algorithm. In case one of these values is exceeded, an error has occurred and the error handling algorithm takes control over the system. There can not be an universal process for handling errors, because every robot has different functions and requirements. For the hexapod it is essential to identify occurring problems early enough in order to have the chance to continue its regular work.

5.5. A learning System

If an autonomous working hexapod is supposed to operate in the same region for a longer period of time, it would be highly innovative to make him learn certain details of this region like the shortest path and the combination of the most effective gaits to an already known destination.

A prerequisite for this is the availability of memory. When finding out the best solution to a problem, a so called evolutionary algorithm can be applied. This is a controlling algorithm for a certain problem, which is developed by itself. This procedure is called genetic programming and can lead to quite impressive results (Banzhaf and Ziegler 2005).

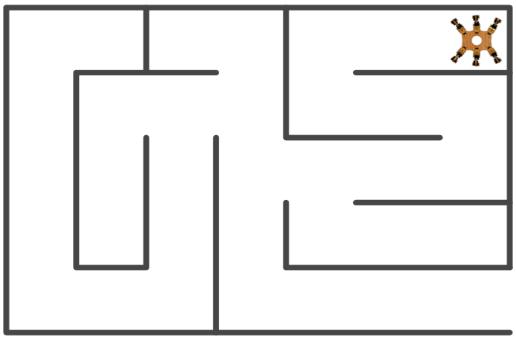

Figure 9: The Hexapod has to escape the Maze

The functionality of genetic programming can be best described by an example. Let us have a look at figure 9. A motion sequence with the quickest way out of the maze is wanted and the hexapod has to memorize this way in order to get out much faster the next time. For this reason, the hexapod needs some basic commands, which are processed in a recursive kind of way. These are moving forward, left, backward and right. Now the hexapod applies these commands always in the same order starting at a defined position, which is the right upper corner in this example. After every successful execution of one command, this step is buffered and the hexapod starts again with the first command from the new position. If the execution of one command is not possible, because there is a wall in front of the robot, the next command is tried out. If this is successfully, this step is buffered, and the procedure begins with moving forward again from the new position. If it comes to the problem, that no direction is possible from a certain position, the hexapod moves a step back and removes this step from the buffer. And now the next command from this position is tried out. In this way, the hexapod walks through the maze until it reaches the exit in the right bottom corner. After the exit is recognized, the buffered steps are memorized permanently as the way out of this particular maze.

This example is supposed to show the principle how to make a robot learn. Many other problems can be solved with genetic programming. It would also be possible to find the best way of walking in general with this principle. The requirements to enable genetic programming are to provide a set of basic commands or processes, which are needed to build the higher desired process.

6. CONCLUSION

The prior observed use cases of a hexapod walking robot should now allow significant statements about the requirements to robotics in order to make cybernetic processes possible and to work in an autonomous kind of way.

You always have to be aware of the most important components a cybernetic control cycle consists of. Firstly, some kinds of sensing elements to grasp the required information. Secondly, the feedback loop in order to compare the measured data with the input. And thirdly, a regulator, which is responsible for calculating the appropriate control signal for the system in order to adjust the regulation deviation to zero. These are just the basic prerequisites to enable a cybernetic process at all. But it is much more important to understand the cybernetic principles and be able to think in an interconnected kind of way. You need to be able to recognize subsystems within a bigger system and convert them into self-controlled elements consisting of one or more cybernetic control cycles. With this strategy you can reach a high flexibility and a good stability of the system as well. It is also essential to identify the best way of cross-linking between these subsystems. In this way, the whole system looses complexity and the robots supervising control algorithm can be able to handle the information flow between the subsystems.

As you can see in the shown examples it can be possible to implement an autonomous operating robot, but it also means a huge amount of effort. No matter how far developed a robot is, there will always be certain limitations in its autonomy. A completely autonomous acting robot would need the ability to react to every problem appropriately and accurately timed. But unfortunately, this is only restricted possible nowadays. The rising number of sensing elements and control units are the reasons for this limitation. So the main interest should be in developing robots, which are able to react to as many different kinds of problems as possible or to to make them best suitable for specific applications.

Basically, you can say that cybernetic processes of all kinds have to follow specific rules in order to keep a system under control. By modeling concrete use cases of a specific platform in this work, it has been shown that cybernetics is an interdisciplinary science, which can be applied to many different areas. Furthermore, by simulating a robots behavior within these scenarios the needed effort for operating in a cybernetic kind of way could have been estimated.

As we can see, it is not constructive to concentrate only on the technical matters when developing robots. It is much more important to have correct and powerful organization structures, locomotion sequences, materials, and so on. You can obtain these things from many other sciences and then apply them within the robot developing process.

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