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Designing the NAO Body

Controlling the Structures of the Body

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The study aims to design a more flexible body of NAO robot. We focus on the motor of the NAO robots. But at first, we need to know how a humanoid robot works, and what can be improved at this step. We also need to know the similar kinds of robots existing now, and what are they drawbacks and what are they strong points. Before we analyze the motor, we need to know what we can do with the NAO robot comparing to other robots. Since the motor is the heart of the humanoid robot, so first we should know how it works, and what kinds of motors exist in now. And also we need to know which motor we used in the NAO robot, and what we could do to the motor, what kind of aspects we can improve in it.

The method is using calculation to try to get better statistics which can be applied into practice. Matlab was chosen which is software we can do make statistic visualization and also to analyze the statistic we get, and also to calculate the availability of the motor which is chosen to be used in the NAO robot. In this thesis, we expand the research step by step.

The result is better statistics, but before it can be put into application, it should be considered in many other aspects.

Keywords	NAO robots, humanoid robots, motors, control system.

Contents

1 Introduction

The purpose of this study is mainly to research how to design the body of the NAO robot, and if there are any improvements can we do to the NAO. For example, how to make it move faster, how to make it sense more quickly, or how to make it more flexible rather than at previous. Now, when you give a command to NAO, it will take a little bit longer time from hearing the command till the reaction. Also the movements are kind of stiff. The reason for these issues is studied through the structures of the NAO body and also other humanoid robots, comparing the differences from between them, so as to find the improvements. Maybe we can improve the smaller feet, or we can add more gears in the elbows, and also maybe we can do the improvements on the motors.

NAO robots is a humanoid robot, which looks like a human. The head of NAO is an induction area, when you touch his/her head, he/she will give some reactions to you, such as nodding or shaking. The ears actually are loudspeakers, and it can also accept sound outside. The eyes actually are cameras. The switch is on the heart of the body, which is a circle button. As far as now, we know that NAO can communicate with you in some simple words, and it can shake hands with you, it can walk, sit and stand up. Even more, it can speak several languages and it can play Kungfu.

The NAO robot is shown below, in figure 1.

Figure 1 NAO robot

2 Introduction of NAO robot

2.1 About NAO

The height of the second generation of NAO is 120 centimeters. NAO is a humanoid robot, and it has likable appearance, it can also interact with human beings. NAO is a type of humanoid robot which is most being applied into academic sector in the world-wide. Aldebaran Robotics company let the technology of NAO open to all the higher education projects, and they established the foundation for the research of the robot and also the teaching related to the robots in 2010. The applications of NAO are based on that it can be done with visual programming through the existing directive block, so it is probable to discover any kind of areas for users.

Also, it can reach different effects through different complexity degree of programming. Robots teaching is very interesting, since it can challenge and inspired the imagination of children. NAO as the helper of teaching, will creates an unexpected future for the way of education. Over 5000 NAO have been bought by 550 universities among 50 countries as research tool. For example, Harvard University and Brown University(USA), Wales University(UK), Freiburg University(Germany), Tokyo University(Japan), Nanyang Technology University(Singapore), Hongkong University(China), Zhejiang University(mainland China) etc. Universities are not only applying the NAO into the robot research, humanoid, engineering, mathematics, physics and internet technology areas, but also applying it into sociology and health care areas.

The research program which NAO can join include voice recognition,video processing, mode recognition, autism treatment, multiple agent system, automation, signal processing, general movement and route planning. The hardware of NAO are all the latest technology, it ensures the fluency of the movements, and it is equipped with many kinds of sensors. What's more, NAO can be programmed with the system of Linux, Windows or Mac OS, and it can provide the complete software with instruction. The special aspect of NAO is it used embedded processor of Linux, using C++ or Python language to control, its height almost 77 centimeters. Besides, NAO has an open programming model in the varieties programming platform, so different software models can interact with each other better. No matter the level of the users, it can be programmed for NAO through image editing platform. [1].

2.2 Application of NAO

2.2.1 NAO in the RoboCup

In the July of 2007, NAO was chosen as standard platform by committee of RoboCup, as inheritors of Sony robot dog Aibo. RoboCup is divided in different match groups. In the “Platform Standard League”, each group used the same robot to compete, all the group only needs to compete the level of software development. The operation of robots is totally automated, without controlling from outside, no human being nor computer. The first place appearing for NAO is in the Suzhou, China, the following appearing is in the Graz competition in the Austria.

2.2.2 NAO in the Shanghai 2010 World Expo

NAO was as High-end technology ambassador for French appearing in the Shanghai World Expo in 2010. It was settled on two French pavilion and it showed the leadership and achievement of France in the area of technological innovation. NAO was a mascot of the French Paris pavilion which was Urban Best Practice Area, there were two NAO robots as tour guides for visitors and welcomed them. In the French pavilion, there were 7 robots in total to give the performance for the visitor in the small displays. On the 21st of the June, 20 of NAO robots had given the perfect performance of automated collective dance which lasted almost 10 minutes in French pavilion, making a new humanoid robot’s history. The performance was divided in 3 pieces, including the famous symphonic work ‘Bolero’ by the French composer Maurice Ravel, perfectly showing the stability, flexibility and rhythm movements of NAO.[2].

2.3 Functional Characteristics of NAO

When NAO starts study new things, it is like the human baby. NAO also can infer the changes of the human emotion through studying body language and expressions, with the time flies, ‘knowing’ more people and can tell the difference between different behavior and faces. NAO can express the emotion of anger, fear, sadness, happiness,

exciting and being proud, when they face some intense situation which they can not handle, and if there is no one to communicate with, it will be even angry about that. It 'brain' can remember what it has experienced; good or bad.

2.4 Operation of NAO

NAO is very flexible, and it has inertial navigation devices, to keep it stable when it is in the moving model. It can also detective barriers and come around it through ultrasonic sensor, so make it accurate about it is activity. Each foot is equipped with pressure sensor, to know the location of the center of pressure, and to make some improvements to keep itself balance.

2.5 Technical Characteristics of NAO

The highlight specialisation for NAO is the embedded software. Through those software, NAO can do the audio synthesis, sound location, detection of visual image and shapes with colors, detection of barriers(through dual channel of ultrasonic system) and producing visual effect or interacting through many luminous diodes by itself. The materials of the body are industrial plastics. NAO's hands can hold and grab. The charger for NAO is AC 90-230 V/DC 24 V. NAO can work lasting almost 90 minutes. The sound of NAO is made up by 2 loudspeaker and human voice. It has four microphone and language analysis and recognition system. It through 2 CMOS(Complementary Metal Oxide Semiconductor Transistor) to have the visual sense. It connect with IEE 802.11g and Ethernet Port.

3 Comparing with Other Humanoid Robots

3.1 Comparing with Asimo robots

From the functional aspect, there are many DOF(Degree Of Freedom) in the Asimo fingers, but in NAO robot's finger, there is only one DOF. In total, there are 26 DOF in the whole Asimo body, that is for the first generation, and there are 37 DOF in the second generation for Asimo, 57 DOF in the third generation of Asimo. But there are only

25 DOF in the NAO. The number stands for the flexibility, which there is an definition “This number typically refers to the number of single-axis rotational joints in the arm, where higher number indicates an increased flexibility in positioning a tool.”[3]. Let us make it in a easier way to understand, NAO can not grab things by its hands. DOF is as a kernel parameter to the robots.[4].

Asimo is the earliest humanoid robot which has human feet to walk as human. Its speed from 0 to 9 kilometers per hour, almost cover the average human walking speed which is about 4 to 5 kilometers per hour. It can climb stairs and it can walk as ‘8’ number. When it faces some complex routes, it can change its core in advance after its prediction. Asimo can make a turn and turn around, because it has anti-slip, anti-revolving, shock absorption and MWT(Movable Weight Technology), so it can run fast, and stand on one leg. Through lots of sensors, it can react according to the human voice and gestures, and it can keep the same speed as fellow traveler, and it can also avoid barrier, it is equipped with the basic ability of memory and identification.

3.2 Comparing with Atlas Robot

The biggest advantage of Atlas robot is the ability of carry. It can do the carrying in different situations. Atlas can walk through the snowfield and hills, it can walk smoothly through the hillside with full of snow and bumpiness. Besides, it has good balance ability, it can stand still even when it is been kicking and slip, even it was kicked down, it can stand soon. That because it is equipped with laser radar and solid acoustic sensors, and because its company is Google, so it also has the Goggle outdoors position system, and it has already can do the self-navigation indoors and outdoors. From that video, it has powerful ability of target identifying and searching, the tester took away the box several times, Atlas still can locate the box and then complete the mission of holding it up.[5].

3.3 Comparing with Alpha1S Robot

Alpha1S is also a humanoid robot, and it is also a member of complicated structures and highly integration robot family, it has 16 DOF, so when it imitates vividly for the human beings. It is embedded with Bluetooth, so it can be easily controlled, and the stability is very good. With the blue sparkling eyes, so you can know if your instruction has been taken. Alpha1S comes from a Chinese high-tech company, called UBTECH. The core of the robot is the servo, built-in MCU(multi-point control unit) system including servo-controlled system, planetary moderation system, and sensory feedback system. From the surface to the core structures, it is local brand, and it obtained lots of patents. The specialty is the price, it is very cheap, even one of ten prices than the other similar humanoid robots.[6].

3.4 Comparing with Pepper Robot

Pepper is also from Aldebaran Robotics Company, which is the company of NAO, but it is based on Cloud, and it is emotional. The height of it is four inches, and its arms are concise and flexible. When you are going near it, it will stare at you for one second and then stretch itself all around on all sides, it seems like it is watching around. Then it stops, saying ‘Hi’ to you with holding its one hand, and then doing the gesture to let you near it.

The special is ‘emotional’ ability, because it can ‘read’ human emotion through the face expressions and intonation from human beings. It is all based Cloud’s face expressions and voice to complete those tasks. With knowing you more, programmer will know more about how to programming to ‘read’ more emotion, and then Pepper will become smarter.[7].

4 The Body Structure of NAO

4.1 The basic structure for the general robots

Taking an X-ray of NAO, helps knowing NAO better The figure 2 below is showing this.

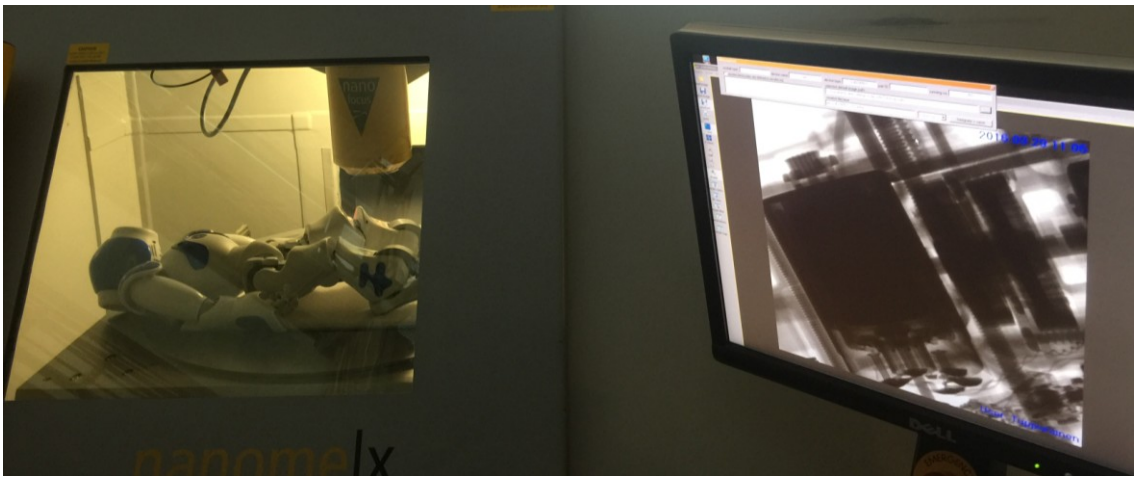


Figure 2 Taking an X-ray of NAO

A robot consists of mechanical, sensor and controlling. These three parts can be split to mechanical structure system, driving system, sensor system, control system, robot-environment interaction system and human-robot interaction system.

4.1.1 Mechanical Structure System

Robots' mechanical structure system consists of body, arms and end-effector. Each part of them has some DOF, forming a multiple DOF mechanical structure system. So according to this, it can be classified as Cartesian coordinate robot, Cylindrical coordinate robot, Polar robot, Articulated robot, SCARA(Selective Compliance Assembly Robot Arm) robot and Mobile robot.

4.1.2 Driving System

Driving system is a kind of device to provide power for mechanical structure system. The kind of drive is different when the power source is different. There are mainly four kinds of drive: Hydraulic type, Vapour-pressure type, Electric type and Mechanical type. Electric drive is the way we use widely today, the characteristic are getting power supply easily, responsiveness quickly, huge driving force, convenient for testing, passing and handling for the signals, and it can be controlled in many different ways, drive motors are always be stepping motor or servo motor, and nowadays, there is also direct drive motor, but it is more expensive and more complicate to control, the retarder which

is matching with always be harmonic reducer, cycloid pin wheel reducer or planetary gear reducer.

4.1.3 Sensor System

Sensor system is made up of sensor-integrated module inside and sensor-integrated module outside, acquiring useful information from inside and outside environment. Using intelligent sensor enhance the motive, adaptive and intelligence level of robot. The sensitive system of human beings is very subtle, but as for the some special information, sensor is more effective than humans'.

4.1.4 Control System

The task of control system is to govern robot completing certain motion and function according to the command and information from sensor feedback. If the robot is not qualified with information feedback, it is a open loop control system; Otherwise, it is closed-loop control system. According to the control principle, it can be Program control system, Adaptive control system and Artificial intelligent control system. Besides, according to the way of motion, it can be Position control and Continuous path control.

4.1.5 Robot-Environment Interaction System

Robot-environment interaction system is a system which can reach the goal that robot can relate and coordinate with equipment from outside. Robot and equipment from outside can be integrated as functional unit, for example, Processing and manufacturing unit, Soldering unit, Assembling unit and etc. Of course there could be many robots integrated as one complicated functional unit.

4.1.6 Human-Robot Interaction System

Human-robot interaction system is a device that human beings can relate with robot and to control robot. For example, the standard terminal of computer, command console, information display board, danger lights and etc.

4.2 The Basic Hardware Parts of Simple Robots

4.2.1 Data Transmission of Robot

A. Cables Transmission

Like USB(Universal Serial Bus) cable, it connects with computer, and it can download program.

B. Wireless transmission

Like Bluetooth, using with Bluetooth, you can communicate with your robot wireless, and it is also useful with robots between. You can use your own mobile phone as an advanced sensor, remote your robot by your mobile phone.

4.2.2 Sensors

There are some basic sensors:

A. Light sensor: It can sense the strength of light from outside. Read the value from infrared emitting diode, you can also turn off the infrared emitting diode.

B. Ultrasonic sensor: It can sense the distance, recognize the object and motion.

C. Voice sensor: It can measure DB(Decibel) and DBA(Decibel adjusted), and it can recognize the voice and volume.

D. Touch sensor.

5 Motors

5.1 Synchronous Motor

5.1.1 Working Principle of Synchronous Motor

This motor consists of two major parts. The first one is stator. Stator of this motor is made up of number of lamination of silicon steel to radius hysteresis and eddy current laws, the cylindrical stator is provided, but there is number of slots. But three phase winding is distributed among this starter similarly that when three-phase power is supplied, a rotating magnetic field is produced. A synchronous speed is rotated for this magnetic field. The second one is rotor. The rotor includes electromagnet. When supplying DC power to the rotor, the rotor's field is excited. After that excitation, it becomes an electromagnet, these two electromagnets are locked with opposite poles which are in the rotating magnetic field magnetically, and so that the rotor will also rotates at same speed with the rotating magnetic field. The rotating flux rotates at very high speed. Because of that, the stator poles will not be locked with the poles of the rotor, also the motor does not work initially.

Synchronous motors are able to run at a constant speed irrespective of the load which is acting on them. They are high efficient machines and they are always put in high-precision applications. Through the interaction between a constant and rotating magnetic field (RMF), it realize the constant speed. Making a constant magnetic field by rotor a synchronous motor, making a revolving magnetic field by stator. Through a three-phase AC supplying, the field coil stator is excited. A revolving magnetic field which rotates at synchronous speed will be made, through DC power supplying,rotor will be excited, and it will act like a permanent magnet, alternatively rotor can also be made of permanent magnet. [8].

Synchronous speed can easily be derived as follows:

$$Ns = 120f/P \quad (1)$$

The unit of Ns is rpm, f is frequency and P is number of poles.

The equation means that when someone control the electricity frequency, the synchronous motor could also be controlled. But when the rotor has no initial rotation, it will be

a quite different situation. The two ends pole will be attracted, and then they will begin to act in the same direction. But because the rotor has some inertia, the speed of the beginning will be very low, at the same time, north pole will replace the south pole of RMF, so it will produce a repulsive force. As a net affect, rotor or synchronous motors are not capable to start with. In order to make synchronous motor self-starting, through pole tips, a squirrel cage arrangement will be fitted. Since the starting rotor field coils are not energized, so with revolving magnetic field electricity is induced in squirrel cage bars, and rotor starts rotating just like an induction motor.

5.1.2 The Working of Alternators

Alternators is able to generate AC power in a specified frequency. So we also call it as synchronous generator. In alternators, through electromagnetic induction, electricity will be produced. In order to generate electricity in a coil, either the coil should rotate according to magnetic field, or the magnetic field should rotate according to the coil. The latter approach is usually used in the case of alternator. An alternator mainly has two parts, one is rotor, and the other one is armature coil. A rotating magnetic flux is produced by rotor, and rotating magnetic flux associated with the rotor induces electricity in the armature coils. Armature coils are stationary. This kind of rotor is shown in figure 3.

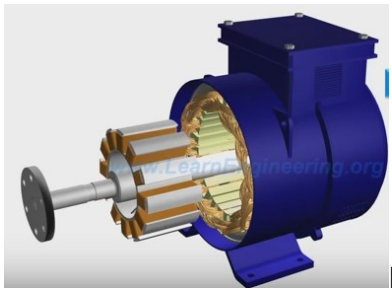


Figure 3 Alternators [9].Copied from Video

To knowing better of its working, consider a rotor with four poles. DC power source activate rotor coils. Magnetic field produced around it as shown in figure 4.

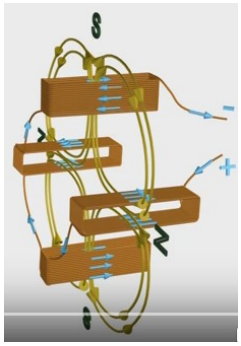


Figure 4 Magnetic field with rotor [9].

Through a prime mover, the rotor is able to rotate. This makes the rotor flux also rotate along with it, at the same speed, such revolving armature coils intersects magnetic flux now, which is fitted around the rotor. An alternating EMF will be generated across the winding. Induced EMF finished one complete cycle when the rotor turns half revolution for this four pole system. It can be concluded that frequency of induce EMF, rotor speed and number of poles are related through following relationship:

$f\,(\text{Hz}),\ N\,(\text{rpm}),\ P$

$$f = \frac{PN}{120} \quad (2)$$

It is clear that producing frequency electricity is synchronized with mechanical rotational speed. For producing 3 phase AC current, two more such armature coils which are in 120 degree phase difference with the first is put in the stator winding. One end of these three coils are star connected in general, and from the other ends, three phase electricity is drawn. Obviously from this equation, for example, a 4-pole rotor should run at following RPM to produce 60-hertz electricity. This huge RPM will induce a tremendous centrifugal force on poles of the rotor, and it may fail over the time mechanically. In generally, salient pole rotors have 10 to 20 polls, which needs lower RPM. Salient pole rotors are usually used when the prime mover rotates at relatively lower RPM. Pole core is used to transfer the magnetic flux effectively, and they are made with thick steel lamina. Such insulated lamina reduce energy loss because of eddy current formation. Armature winding of three-phase, 12 poll system is shown in figure 5.

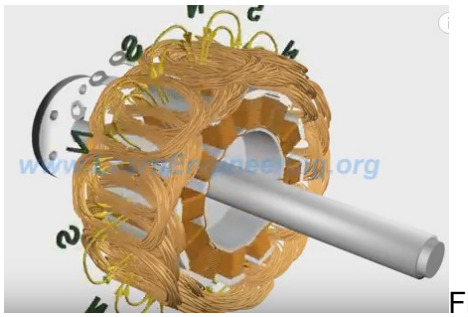


Figure 5 Armature winding [9].

A stator core is usually used to enhance the magnetic flux transfer. Through a pair of slip rings, DC current is supplied to rotor, and it is supplied from a small DC generator which is fitted on the same prime mover or an external source. This kind of alternators are called self excited. Generator terminal output voltage will change with variation of load. It is expected to keep the terminal voltage within a specified limit. An automatic voltage regulator gives help in realizing this. By controlling the field current, voltage regulation can be realized easily. If the terminal voltage is below the expected limit, AVR increases the field current, thus the field strength. This will increase the terminal voltage. The reverse will be done if terminal voltage is high. [10].

5.2 Induction Motor

5.2.1 Induction Motor Construction

Here is the induction motor below, in figure 6.

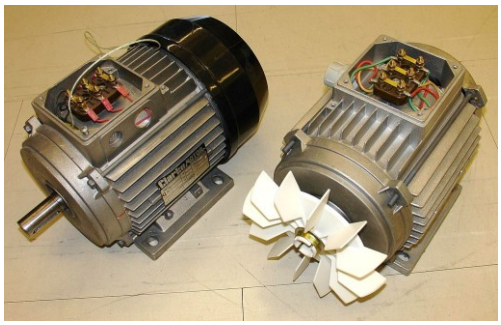


Figure 6 Induction motor

Stator is the main part of the induction motor. And frame is the outer most part of the stator, to provide mechanical production and support for the winding are the purpose for frame. Insulated electrical bindings is the next sub-part of the stator, these electrical winding consist of copper wire insulated with varnish. These are fitted into insulated slotted lamination which are made from steel to reduce the effect of eddy currents, another main part of the induction motor is rotor. The rotating part of the motor id rotor. According to the rotor structure, there are two types of rotors, one is squirrel cage rotor and the other one slip ring rotor.[11]. Here is the squirrel cage rotor, in figure 7.

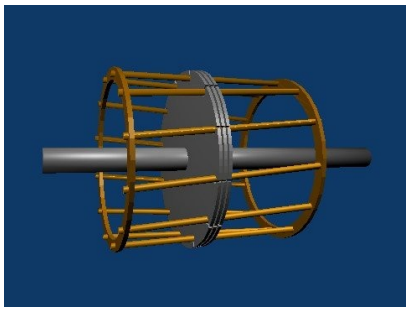


Figure 7 Squirrel Cage Rotor

5.2.2 Three-phase Squirrel Cage Induction Motor

Induction motors are the most commonly used electrical machines. They are cheaper rugged and easy to maintain when compared to other alternatives. It also has two main parts, stator and rotor. Stator is a stationary part and rotor is the rotating part. Stator is made by stacking thin slotted highly permeable steel lamination inside a steel or case-iron frame, winding passes through slots of stator. When a three-phase AC current passes through it, it will produces a rotating magnetic field. Considering a simplified three-phase winding with just three coils. A wire carrying current produces magnetic field around it. Now, for this special arrangement magnetic field produced by a three phase AC current will be at a particular instant. With variation in AC current, magnetic field takes a different orientation.[12]. For these three position,it is shown below in figure 8.

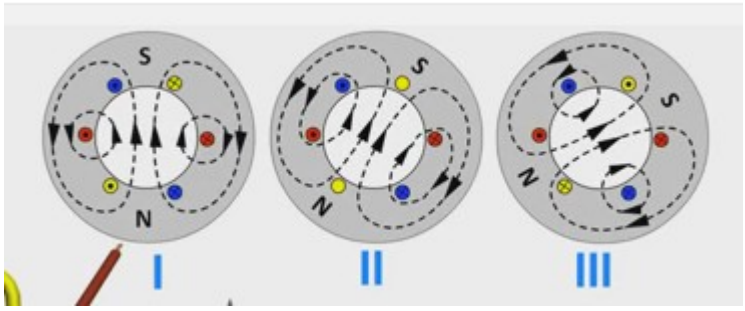


Figure 8 Three position [13].Copied from Video

It is like a magnetic field of uniform strength rotating. A magnetic field is at a synchronous speed.

5.2.3 Single-phase Induction Motor

Single-phase induction motor only needs one power phase for its operation. A single-phase motors have main components:a rotating part which is a rotor and a stationary part which is stator. It has two parts, one main winding and one auxiliary winding. Auxiliary winding is put perpendicular to the main winding. In auxiliary winding, a capacitor is connected. A single phase induction motor is simply working, just put one rotor which is already rotating inside such a magnetic field. You can find the rotor will keep on rotating in the same direction.[14].

5.3 The Operation and Construction of Commercial DC Motor

Here is the simplest DC motor, in figure 15.

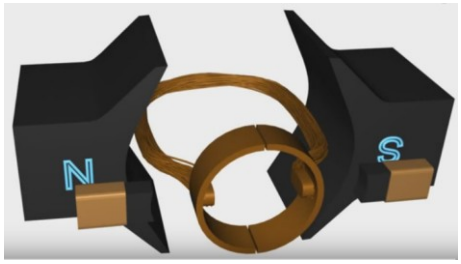


Figure 9 Simplest DC motor [15].

The stator provide a constant magnetic field, and the armature is a simple coil which is the rotating part. The armature is connected to a DC power source through a pair of commutator rings.

5.4 Brushless DC Motor

Recently, brushless DC motors has been used more often to make the operation more efficient, more reliable and less noisy. With the same power output, comparing to brushed motors, they are also lighter. In conventional DC motors, the brushes wear out over the time and may cause sparking, thus the brush DC motor should never be used for operations that demand long life and reliability.

The rotor about BLDC(brushless DC) motor is a permanent magnet, the stator has a coil arrangement as below in figure 10.

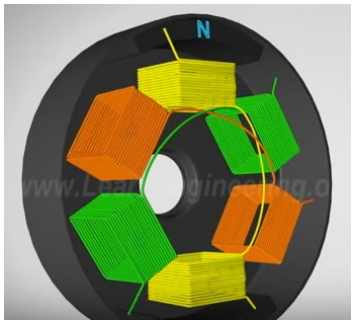


Figure 10 Stator [16].Copied from Video

The coil would energize and become an electromagnet through applying DC power to that. The operation of BLDC is based on the simple force interaction between the permanent magnet and electromagnet. In this condition when the coil A is energized the opposite poles of the rotor and stator, in figure 11 below.

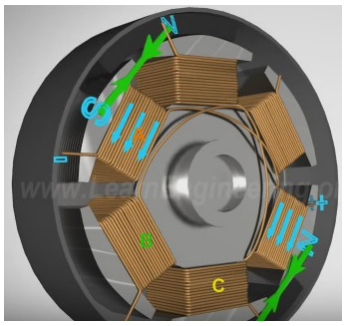


Figure 11 Condition [16].Copied from Video

Coil B is energized with the rotor nears coil A, coil C is energized with the rotor nears coil A, after that coil A is energized with the opposite polarity, this process is repeated and the rotor continues to rotate. A humorous analogy to help us remember it which is to think about BLDC operation like the story of the donkey in the Carrot Act. When the donkey tried hard to reach the carrot but the carrot keeps moving out of reach. As the figure shown below in figure 12.

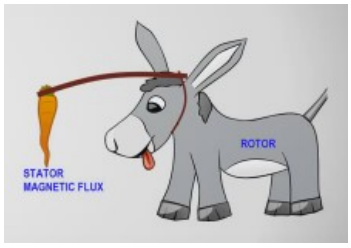


Figure 12 Carrot Act [16].Copied from Video

It still has one drawback even though this motor works, it is easy to find that only one coil is energized at any instant, the two dead coils reduce the power output of the motor greatly. There is also a way to resolve this issue, with the rotor is in this position, along with the first coil which pulls the rotor, you can energize the coil behind it, in such a way that it will push the rotor. At this time, a same polarity current is passed through the second coil. The effect of combination produces more torque and power output from the motor. The combined force also ensure that a BLDC has a constant torque nature, with this configuration, two coils need to be energized separately. But through making a little modification to the stator coil, this process can be simplified, connecting 1-3 N on the coils together when the power is applied between coils A and B, note that the current flow through the coil, as the figure 13 shown below.

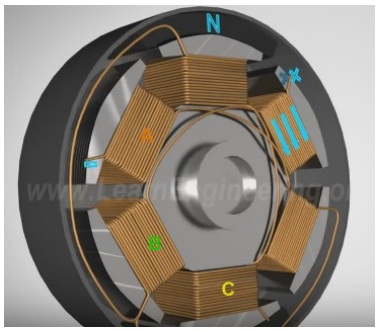


Figure 13 Current flow [16].Copied from Video

That is how BLDC works, it is just like the separately energized state. But there are still some intriguing doubts. For example, knowing which stator coils to energize, and which to energize so that to get a continuous rotation from the rotor. In BLDC, using an electronic controller for this purpose, a sensor decides the position of the rotor. And based on this, the controller determines which coils to energize. Mostly, a HALL effect sensor is used for this purpose. The BLDC design which we have discussed so far is known as out-runner type, in-runner BLDC design is also available in the market. [17].

6 Controlling system

6.1 General Introduction of Control Theory

Then we need to clarify what is the controlling, and what is the control theory. It should have a plan or model of what it expects to finish before controlling a robot or other complex intelligent machine. For example in many plans, it always requires modification at the moments of the beginning of its execution, although it is essential.Its servos is often referred to as the rabbit and the position of the actual robot or servo is referred to as the hound.

Actually control theory describes the science of control system which is equipped with new concept and new thought in theoretical research result and other areas, especially in the high-tech areas researching result, but in the civic area is heavily out of line in actual life.Control theory can be divided in two, one is modern control theory and the other one is classical control theory.

Classical control theory can be also called as automatic control theory. It has been in existence for a very long time. In engineering courses, it have traditionally taught mathematical techniques, which is involving poles, zeros and very abstract mathematics that describes the conditions under which a control can be designed with optimal performance.

One of the core of modern control theory is optimal control theory. This theory has been applied in the beginning of the 1960s. This changes the old design way which is the heart of stability and dynamic quality in the classical control theory, thinking of the system performance during the working period, finding optimal control law, so that greatly improved property of system. Optimal control theory has obvious result in the areas of engine fuel and rotational speed control, track correction and minimum time control, safe landing control and so on.

The other core of modern control theory is optimal-estimation theory (Kalman filtering). It can solve random disturbance and stochastic control in the aircraft control. Kalman filtering breaks the bounded of winer filtering, and it can be adapted to multi-input and multi-output system, stable or unstable random process, widely applied in orbit measurement and track of aircraft, controlling interception and meeting and so on.[18].

Modern control theory includes many subjects, mainly in linear system theory, nonlinear system theory, random control theory,optimal control theory and so on.

6.2 The Evolution of the Modern Control Theory

A. Intelligent Control

Intelligent control is a combination of artificial intelligence and automatic control.It is a kind of intelligent machine that can be driven independently without humans' intervention to achieve the target of automatic control. The attention of intelligent control is

attached to the expressions of mathematical formulas, calculation and processing, instead of the identification on the task and model descriptions, symbols and environment, as well as the design and development of knowledge base and inference machine. Intelligent control is used for the production process, making the experience that computer system imitates experts or skilled operators to establish the generalized model based on knowledge, adopt symbolic information processing, heuristic programming, knowledge representation and self-learning, reasoning and decision-making and intelligent technology to understand, judge, forecast and program to the external environment and the system process, making the controlled object achieve certain intended purpose.

The theoretical basis of intelligent control is an intersection of artificial intelligence, control theory, operations researches and system science. The major characteristics of intelligent control are as follows:

-Meanwhile, it is equipped with the mixed control process which is represented by non mathematically generalized models and the mathematical models.

-The core of intelligent control is in high level control, namely the organization level. Its main task is to organize the actual environment or process.

-The information obtained by system does not only lie in mathematical information. More important are the text symbols, images, graphics, sound and other information. [19].

Intelligent control is in the process of development; there are still many problems to be studied:

1. The discussion on the new intelligent control theory

2. Using voice control

3. Improve the learning ability and independent ability of the system

4. Take advantage of nonlinear technique available to analyze the characteristics of closed loop system

5. The realization of intelligent control

B. Nonlinear control

Nonlinear control is one of the important basic problems in complex control theory, and it is also a difficult project. Its development is almost parallel to the linear systems and the development of nonlinear systems. Mathematical tools is a very difficult problem. Taylor series expansion is not applicable for some cases. The phase plane method in the classical theory is only applicable to the two order system, which is suitable for the description function method of the higher order system containing a nonlinear element. Because of the lack of systematic and general theories and methods in the study of nonlinear systems, the comprehensive methods have been developed.

They are as follows:

1. Lyapunov method: it is the most perfect, general nonlinear method so far. But because of its generality, there lacks construction in analyzing stability or calming the synthesis.

2. Variable structure control: due to its sliding modes which possess the in-variance of disturbance and perturbation, which is paid attention in 1980s, it is a practical method for the synthesis of nonlinear control.

3. Differential geometric method: in the past 20 years, differential geometric method was the mainstream of nonlinear control system research. Its structure of nonlinear system analysis, decomposition, and structure of the relevant control design brought great convenience. Using the method of differential geometric method to research the nonlinear system is the inevitable outcome of the development of modern mathematics. As the Italian professor Isidori pointed out: "the results obtained with the method of differential geometry nonlinear system, like in the 1950s by Laplace transform and theory of functions of a complex variable of single input single output system research, or linear algebra of multi-variable systems research." But this method also has its disadvantages, which is reflected in its complexity, non hierarchical, quasi linear control and space measurement that is destroyed. [19].

Recently some scholars have proposed the introduction of new, more profound mathematical tools to explore new directions, such as: differential dynamics, differential topology and algebraic topology, algebraic geometry, etc.

C. Adaptive control

Through Adaptive control system conducts continuous measurement system of input, state, or output parameters, gradually it can understand and grasp the object, then according to the obtained information according to certain design method to make a decision to update the structure and parameters of the controller to adapt to environmental changes and reach the desired control performance index.

There are three basic functions in terms of adaptive control system:

1. The structure and parameters of the object are identified so as to precisely establish the mathematical model of the controlled object.

2. A control law is given to achieve the desired performance of the controlled system.

3. Parameter of automatic correction controller. Therefore, the adaptive control system is mainly used in the random system which is unknown to the process model or the process model structure is unknown but the parameters are unknown.

The types of adaptive control system mainly include self-tuning control system, model reference adaptive control system, self optimizing control system, learning control system and so on. Recently, adaptive control of nonlinear systems, adaptive control based on neural networks have been paid attention to, and some new methods are proposed. [19].

D. Robust control

An essential issue that process control is confronted with is that the model is uncertain.The uncertainty of the model is mainly solved by the robust control, but there are different processing methods with adaptive control method. The basic idea of adaptive control is used to identify the model parameters, and then design the controller. The adjustment of the controller parameters depend on updating model parameters, which can not be taken into account in advance. Robust control designs a controller based on uncertain information in the design of the controller, which can meet the performance requirements when the parameters are not sure.

Robust control system considering the uncertainties of system can be described by model sets. The model of system is not single, which can be any of the elements in the model sets. But in the design of the controller, the requirements of elements in the model sets can be met. One of the main problems of robust control is robust stability. [19].

There are three kinds of methods currently:

1. When the system is described by state matrix or characteristic polynomial, the central problem is to discuss the stability of polynomial or matrix.

2. The Lyapunov method is a useful tool for the emergence of the state space model.

3. The representative is the Hoo control as to the issue of researching from transfer function. It is used as the validity of the robustness analysis. The external disturbance is not assumed to be fixed, rather than bounded. This method has been used in engineering design, such as the Hoo optimal sensitivity controller design.

E. Fuzzy control

Fuzzy control with the help of fuzzy mathematical simulation of human thinking method, the process operator's experience to sum up, the use of linguistic variables and fuzzy logic theory for reasoning and decision-making, control of complex objects. Fuzzy control is not to refer to the controlled process is fuzzy, nor does it mean that the controller is uncertain, it is the representation of knowledge and the concept of fuzziness, it is completely determined to complete the work.

Since the 1974 British engineer E.H.Madam first fuzzy set theory is used for the control of the boiler and the steam engine, open up the new area of fuzzy control, especially for a large delay and nonlinear and so difficult to establish accurate mathematical model of complex system, through computer to realize fuzzy control can often get very good results.[19].

The types of fuzzy control are as follows:

1. Once the fuzzy control table is determined, the control rules are fixed.

2. Adaptive fuzzy controller, in the operation of automatic modification, improvement and adjustment of the rules, so that the control process of the control effect of continuous improvement, to achieve the desired results

3. Intelligent fuzzy controller, it, artificial intelligence and neural network together, realize the comprehensive information processing, so that the system has flexible reasoning mechanism, heuristic knowledge and rules said, with different levels and of various types of control rules

The characteristic of fuzzy control is that it doesn't need accurate mathematical model, it has strong robustness, good control effect, easy to overcome the influence of nonlinear factors, and the control method is easy to control. Recently, it was proposed that the neural fuzzy Inter3 fusion control model, that is, the fusion structure, fusion algo-

rithm and control for the integration of design. Some people put forward the use of homo-type BP network memory fuzzy rules, in order to "associate" the use of these experiences.

Fuzzy control problems to be further studied: evaluation of the fuzzy control system function, stability, optimization problem; nonlinear complex system fuzzy modeling, fuzzy rules and the establishment of fuzzy reasoning algorithm research; find out to follow the general design principles.[19].

F. Neural network control

A neural network is a network consisting of a simple unit of a neuron that can be adjusted by a parallel structure. There are many kinds of neural networks, which are commonly used in the control, such as multi-layer forward BP network, RBF network, Hopfield network and adaptive resonance theory model (ART).

Neural network control is a new control and identification method using neural network to simulate the human brain from the mechanism. The neural network can act as an object model in the control system, but also can be used as a controller. [19].

Common neural network control structure:

1. Parameter estimation adaptive control system
2. Internal model control system
3. Predictive control system
4. Variable structure control system

The main characteristics of neural network control is: can be used to describe any nonlinear system; for nonlinear system identification and estimation; has the adaptive abil-

ity for complex and uncertain problems; rapid optimization ability; with distributed storage capacity, realize the online or offline learning.

Recently, it was proposed to achieve a multi-resolution stereo collaborative algorithm based on Hopfield network, which is automatically completed by the coarse to fine, until the whole resolution of the matching and the establishment of [5]. Some people put forward a kind of network self organizing controller, using the steepest gradient descent learning algorithm, which is applied in nonlinear tracking control [6]. The problem that needs to be further discussed in the future is to improve the learning speed of the network, and put forward a new network structure, which can be used to control the specific neural network. [19].

G. Real time expert control

Expert system is a program system which has a considerable expertise and experience, it applies the technology of artificial intelligence, reasoning and judgment according to provide a a or a plurality of human expert knowledge and experience, simulation of human experts in the decision-making process, to address those needs expert decision of complex problems. Is the essential difference between expert system and conventional computer programs: the expert system to solve the problems generally do not have the solution algorithm, and tend to make a conclusion on the basis of incomplete, imprecise or uncertain information.

Real-time expert system application of fuzzy logic control and neural network theory, melt into the expert system for adaptive management of an object or process comprehensive behavior and automatic acquisition of process variables, explain the control system's current status and prediction of the future behavior, diagnosis may be the problem, and constantly revised and implement control plan. Real-time expert system has inspired, transparency and flexibility characteristics, has in the aerospace test command, industrial furnace, blast furnace hot stove diagnosis get widely used. At present, the problem of further research is how to use simple language to describe the long-term accumulation of experience knowledge, improve the ability of associative memory and self-learning. [19].

H. Qualitative control

Qualitative control refers to the state variable of the system (its value is not a precise value but only know it is in a certain range), the application of qualitative reasoning on the system control variables to make the system in a certain range.

There are three kinds of qualitative control methods:

1. Based on quantitative model, the quantitative model of the system is assumed to be known, and the qualitative model is derived based on the quantitative model.

2. Control based on qualitative rules, its characteristic is the composition rules of the qualitative model by people's experience of qualitative reasoning can be obtained, or obtained by exhaustive state

3. Qualitative control based on qualitative model, which is characterized by qualitative control directly through the study of qualitative model

Qualitative control, fuzzy control, fuzzy control does not need modeling, the control law by experience or adjustment algorithm and qualitative control based on qualitative model, control rule based on the qualitative analysis, fuzzy control is based on the value of accurate measurement of the state, and the qualitative control based on the value of a qualitative measure of the state.[19].

Qualitative control problems: the development of qualitative mathematical theory, the improvement of qualitative reasoning methods, focus on qualitative and quantitative knowledge of the combination of qualitative modeling methods, qualitative control methods; to strengthen the application of qualitative control research.

6.3 Schematic of controlling system

The whole controlling system is shown in schematic graph below, in figures 14, 15 and 16.

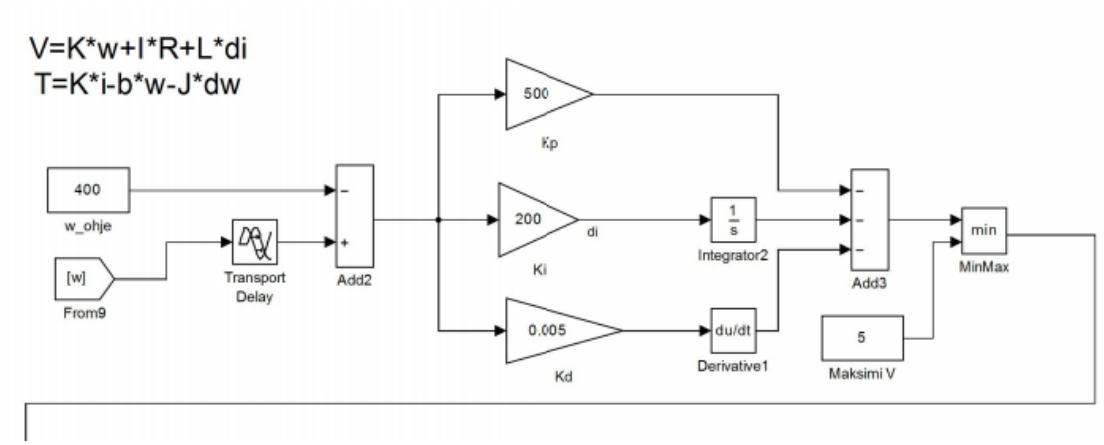


Figure 14 Control system Part 1

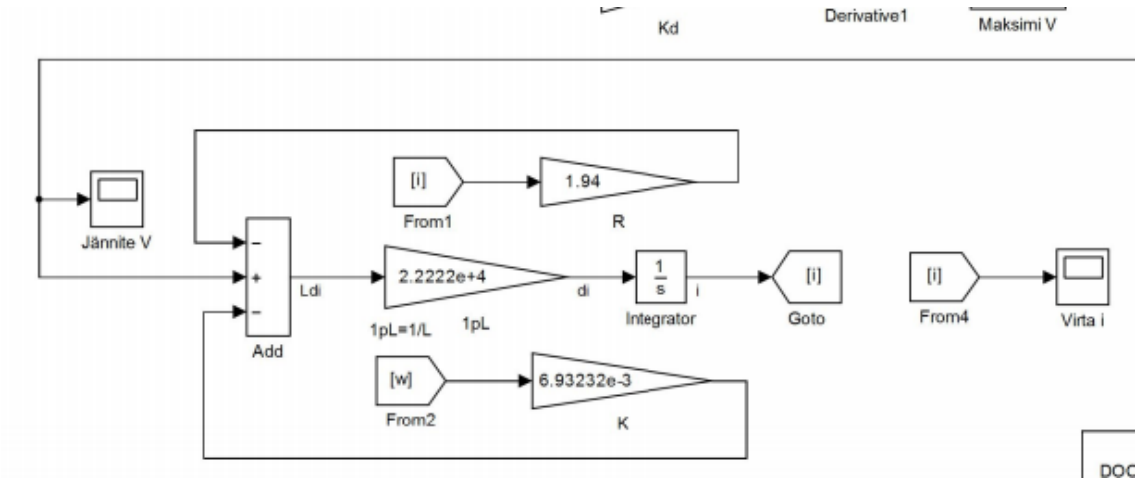


Figure 15 Control system Part 2

This part is how we calculate the voltage, the equation is

$$V = K*w + i*R + L*di \tag{3}$$

from the equation(3) we showed above, we can get that from the left side end, it is

$$-i*R + (+V) + (-K*w) = L*di \tag{4}$$

it is just the transformation about the equation. As the same as how we calculate the torque. Like the equation(5) below,

$$T = K*i - b*w - J*dw \tag{5}$$

Then we have a transformation of that

-T + (+K*i) + (-b*w) = +J*

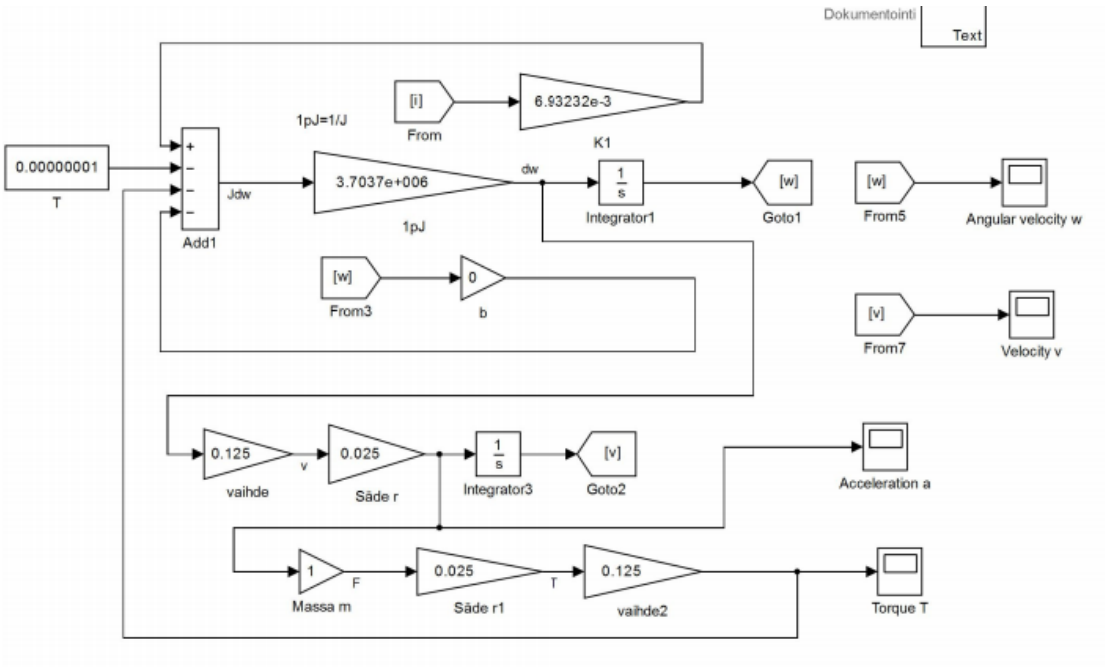


Figure 16 Control system Part 3

All the equations showing in the graph are above.

6.4 Calculation

The calculations are transferring function about w and V, and we use these functions and some known values to get optimisations.

Here is the transfer function A below, in listing 1.

Now we use the file ParametersFor OptimisationV.m

Its contents is shown here. Notice that V=1 and T=0:

```
%V=K*w+i*R+L*di
%T=K*i-b*w-J*dw
%
%Faulhaber DC-Micromotors
%Precious Metal Commutation
%4.2 Watt
%Encoders:IE2
%
%w = radians/s.
%r [rpm] = r * 2pii radians/min = r*2pii radians/(60 sec) =
%        = r*(2pii/60) radians/sec
%    => w = (2pii radians/60 sec)*r tai
%    => r = [60 sec/(2pii radians)]*w.
%
%Back-EMF constant 0,725 mV/rpm
%        = 0.725 mV/(2pii radians/(60 sec))
%        = 0.725 * 60 / (2pii) mV/(radians/sec) = 6.9232
mV/(radians/sec)
%        = 6.93232E-3V/(radians/sec).
%=======================================
%    => Total-back-emf = r * 0,725 mV = w * x
%    => x = (r/w) * 0.725 mV = [60 sec/(2pii radians)]*0.725 mV
%        = 6.9232 mV*sec/radians = = 6.9232E-3 V*sec/radians.
%=========================================================
%
%L=45e-6 H => 1/L = 2.2222e+4
%=========================================
%
%J=2.7g*cm^2 = 2.7/1000 kg * (0.01m)^2 = 2.7*0.0001/1000 kg * m^2
%2.7e^-7 kg m^2
%    => 1/J = 3.7037e+006 /(kg m^2)
```

Listing 1 Transfer Function A

Then we can get those parameters for optimisations below,

L=45e-6，R=1.94，J = 2.7e-07,

J_L=M*r^2/a^2=9.77e-06,

M=1kg, 1/a=0.125, r=0.025m,

J_{TOT}= J+JL=1.004e-05，

K=6.9232e-3，b=0，T=0，V=1

(L=Inductance,R=Resistance, K=Constant of voltage,b=constant for velocity proportional torque, T=Load torque, V=Voltage, M=mass of the cart, r=radius of the wheel, a=reduction ratio of the gear.)

Then we get those functions:

a_1=-L*T, a_0=K*V-R*T b_2=L*J_{TOT} , b_1=R*J+L*b, b_0=K^2+R*b,

num=a1*s+a0,

denum=b2*s^2+b1*s+b0,

sys=num/denum.

pidtool(sys) (it's just a command in Matlab, p is percent control, i is integral control, d is differential control) according to the numbers above, we can calculate them.

Here is the transfer function B, in figures 17.

$$V = K\omega + iR + L(di/dt)$$
$$T = Ki - K\omega - J(d\omega/dt)$$
$$\Rightarrow V = K\omega + IR + LsI$$
$$T = KI - K\omega - (J + J_L)sW$$
$$\Rightarrow I = \frac{T + b\omega + s(J + J_L)\omega}{K}$$
$$\Rightarrow V = K\omega + (R + sL)\frac{T + b\omega + s(J + J_L)\omega}{K}$$
$$V = K + \frac{R + sL}{k}[b + s(J + J_L)]\omega + \frac{R + sL}{K}T$$
$$\Rightarrow \omega = \frac{V - \frac{R + sL}{K}}{K + \frac{R + sL}{K}[b + s(J + J_L)]}T$$
$$\omega = \frac{KV - RT - sLT}{K^2 + Rb + sR(J + J_L) + sLb + s^2L(J + J_L)}$$
$$\omega = \frac{-sLT + KV - RT}{s^2L(J + J_L) + s[R(J + J_L) + Lb] + K^2}$$
$$\omega = \frac{a_1 s + a_0}{b_1 s^2 + b_1 s + b_0}$$
$$a_1 = -LT$$
$$a_0 = KV - RT$$
$$b_2 = L(J + J_L)$$
$$b_1 = R(J + J_L) + Lb$$
$$b_0 = K^2 + Rb$$

Figure 17 Transfer Functions B

Here is the transfer function C, in figures 18.

$$New\_cons\tan t\_is\_gear-ratio\_\rho=\frac{1}{0.125}=8.$$

$$T\_is\_torque\_of\_the\_motor.$$

$$Load\_torque\_is\_T_L=\rho*T.$$

$$w\_is\_speed\_of\_the\_gear.$$

$$V=K*w*\rho+i*R+L*(di/dt)$$

$$T=K*i-b*w*\rho-J_{TOT}*(dw/dt)*\rho$$

$$\Rightarrow V=\rho*K*w+I*R+L*s*I$$

$$T=K*I-\rho*b*w-\rho(J+J_L)*s*w$$

$$\Rightarrow I=\frac{T+\rho*b*w+s*\rho(J+J_L)*w}{K}$$

$$\Rightarrow V=\rho*K*w+(R+s*L)\frac{T+\rho*b*w+s*\rho(J+J_L)*w}{K}$$

$$V=\left(\rho*K+\frac{R+sL}{K}[\rho*b+s*\rho*(J+J_L)]\right)w+\frac{R+sL}{K}T$$

$$\Rightarrow w=\frac{V-\frac{R+sL}{K}T}{\rho*K+\frac{R+sL}{K}[\rho*b+s*\rho*(J+J_L)]}$$

$$w=\frac{KV-RT-sLT}{\rho*K^2+R*\rho*b+s\rho R(J+J_L)+s\rho Lb+s^2\rho L(J+J_L)}$$

$$w=\frac{-sLT+KV-RT}{s^2\rho L(J+J_L)+s[\rho R(J+J_L)+\rho Lb]+\rho K^2+\rho Rb}$$

$$w=\frac{a_1s+a_0}{b_2s^2+b_1s+b_0}$$

$$a_1=-LT$$

$$a_0=kV-RT$$

$$b_2=\rho L(J+J_L)$$

$$b_1=\rho R(J+J_L)+\rho Lb$$

$$b_0=\rho K^2+\rho Rb$$

$$For\_speed\_of\_the\_rotor\_(w_R)\_we\_get:$$

$$w_R=\rho*w=\frac{-sLT+KV-RT}{s^2L(J+J_L)+s[R(J+J_L)+Lb]+K^2+Rb}$$

$$Which\_is\_simply\_the\_previous\_result.$$

Figure 18 Transfer Functions C

When we add all the ρ to the whole text above, we get this again.

Then we get:

L = 4.5000e-05, R = 1.9400,

J = 2.7e-07, J_L=9.77e-06, J_{TOT}= 1.004e-05,

K = 0.0069, T = 0, V = 1,

a_1 = 0, a_0 = 0.0069,

b = 0, b_2 = 4.518e-10, b_1 = 1.94776e-05, b_0 = 4.7931e-05

num = 0.006923,

denum = 1.94776e-05 s^2 + 1.94776e-05 s + 4.7931e-05,

sys = 0.006923 ÷(1.94776e-05 s^2 + 1.94776e-05s + 4.793e-05).

Here is the transfer function D, in figures 19.

$$V = K \cdot \omega + i \cdot R + L \cdot \frac{di}{dt}$$
$$T = K \cdot i - b \cdot \omega - J \cdot \frac{d\omega}{dt}$$
$$\Rightarrow$$
$$\omega = \frac{-sLT + KV - RT}{s^2LJ + s(RJ + Lb) + K^2}$$
$$\omega = \frac{a_1 s + a_0}{b_2 s^2 + b_1 s + b_0}$$
$$where:$$
$$a_1 = -LT$$
$$a_0 = KV - RT$$
$$b_2 = LJ$$
$$b_1 = RJ + Lb$$
$$b_0 = K^2 + Rb$$
$$T = 0:$$
$$\Rightarrow \frac{\omega}{V} = \frac{K}{s^2LJ + s(RJ + Lb) + K^2}$$
$$V = 0:$$
$$\Rightarrow \frac{\omega}{T} = \frac{-sL - R}{s^2LJ + s(RJ + Lb) + K^2}$$

Now the command "pidtool(sys)" in the m-file gives:

Figure 19 Transfer Functions D

According to the statistics above, we can apply those equations and numbers into Matlab, to have the percent, integral and differential statistics analysis of the motor. These figures 20-25 shown below are the View of motor with Matlab.

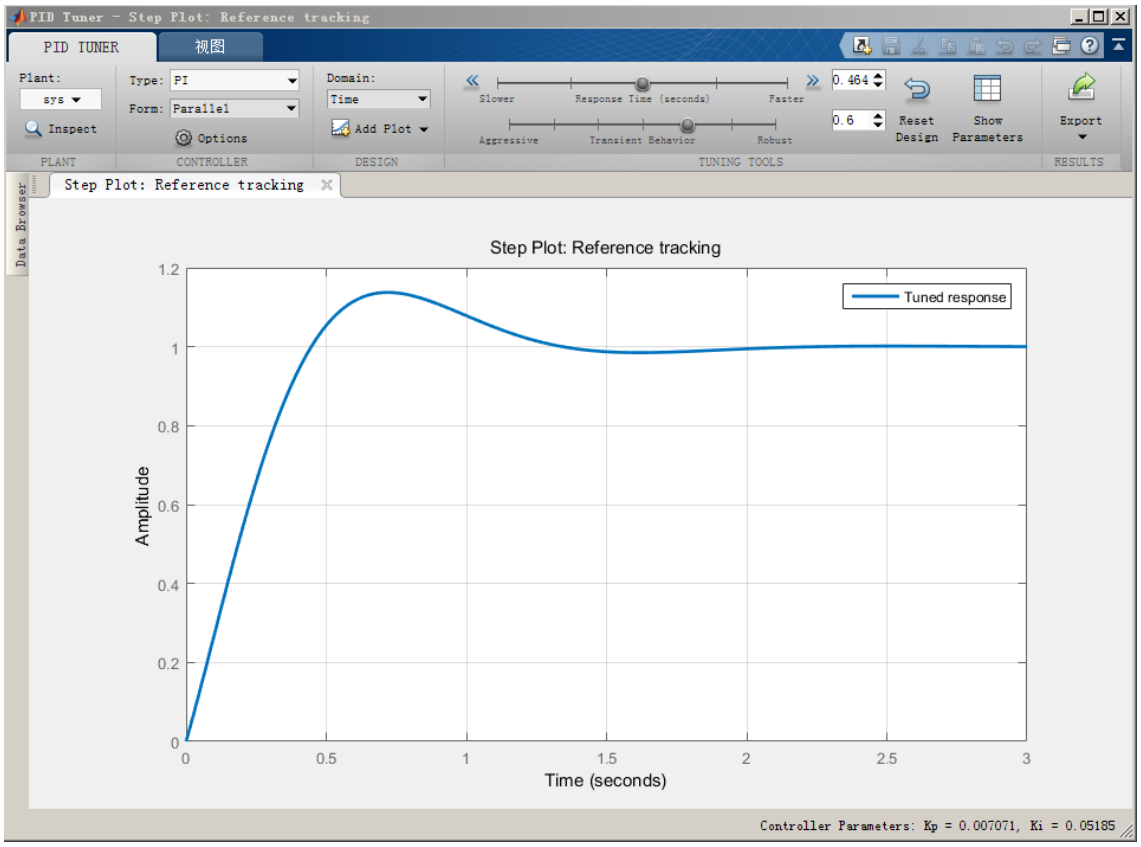
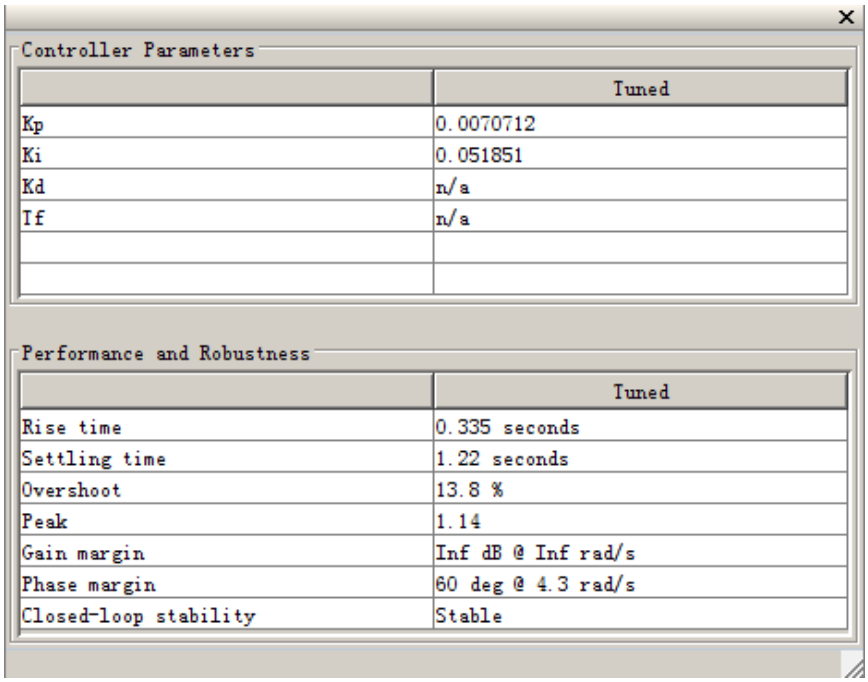


Figure 20 PI view

This is reference tracking of PI view.



Controller Parameters

	Tuned
Kp	0.0070712
Ki	0.051851
Kd	n/a
Tf	n/a

Performance and Robustness

	Tuned
Rise time	0.335 seconds
Settling time	1.22 seconds
Overshoot	13.8 %
Peak	1.14
Gain margin	Inf dB @ Inf rad/s
Phase margin	60 deg @ 4.3 rad/s
Closed-loop stability	Stable

Figure 21 PI parameters

This is the parameters of PI view.

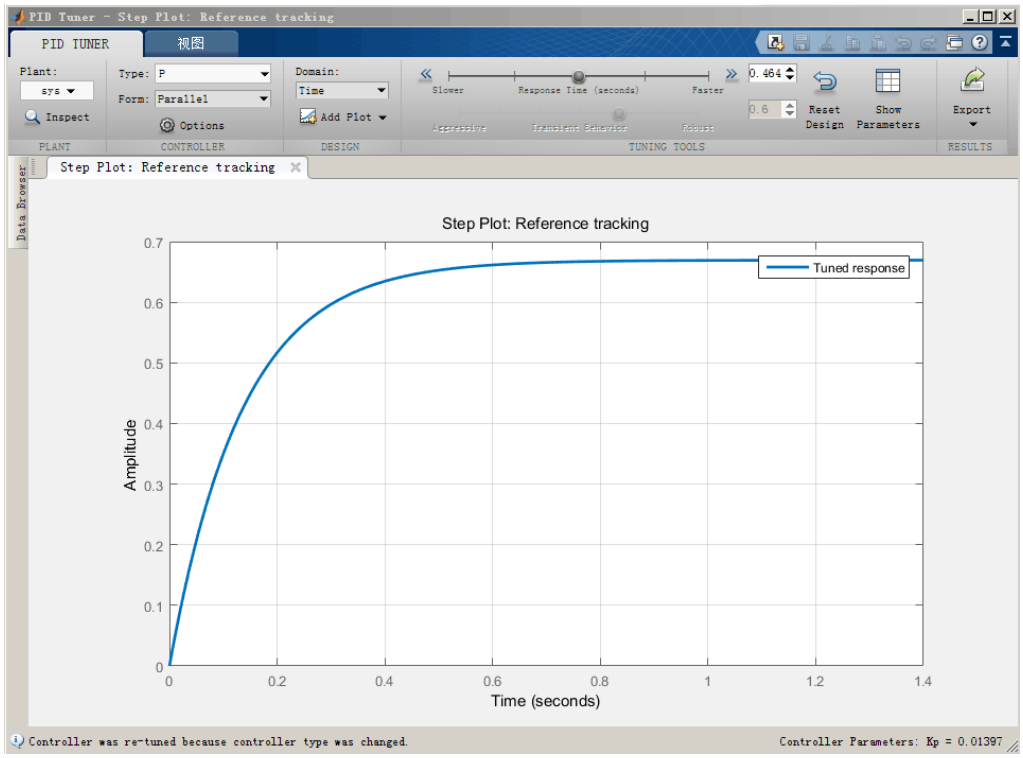
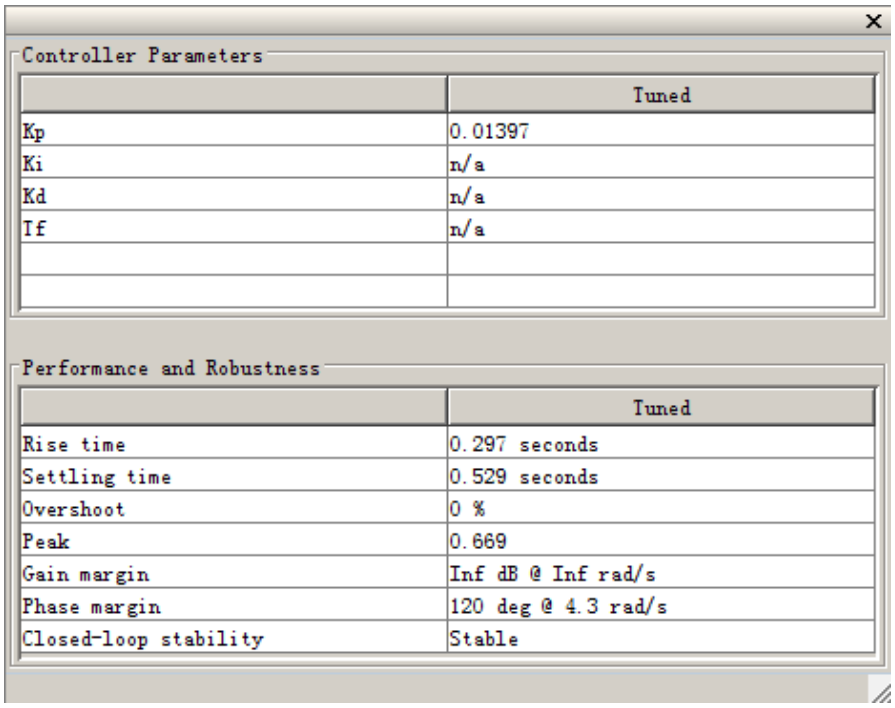


Figure 22 P view

This is reference tracking of P view.



Controller Parameters

	Tuned
Kp	0.01397
Ki	n/a
Kd	n/a
Tf	n/a

Performance and Robustness

	Tuned
Rise time	0.297 seconds
Settling time	0.529 seconds
Overshoot	0 %
Peak	0.669
Gain margin	Inf dB @ Inf rad/s
Phase margin	120 deg @ 4.3 rad/s
Closed-loop stability	Stable

Figure 23 P parameters

This is the parameters of PI view.

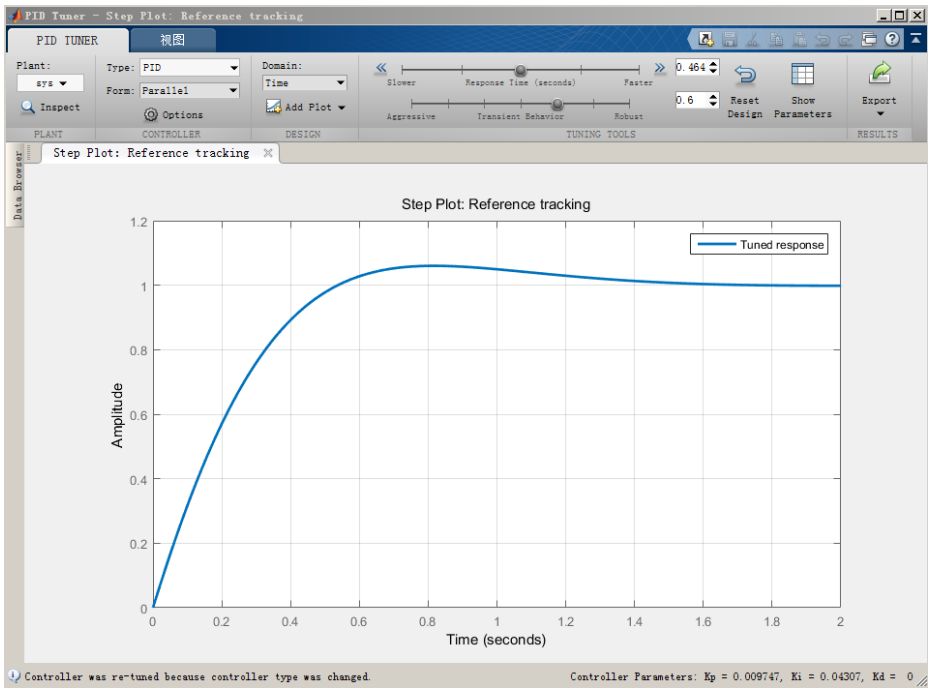
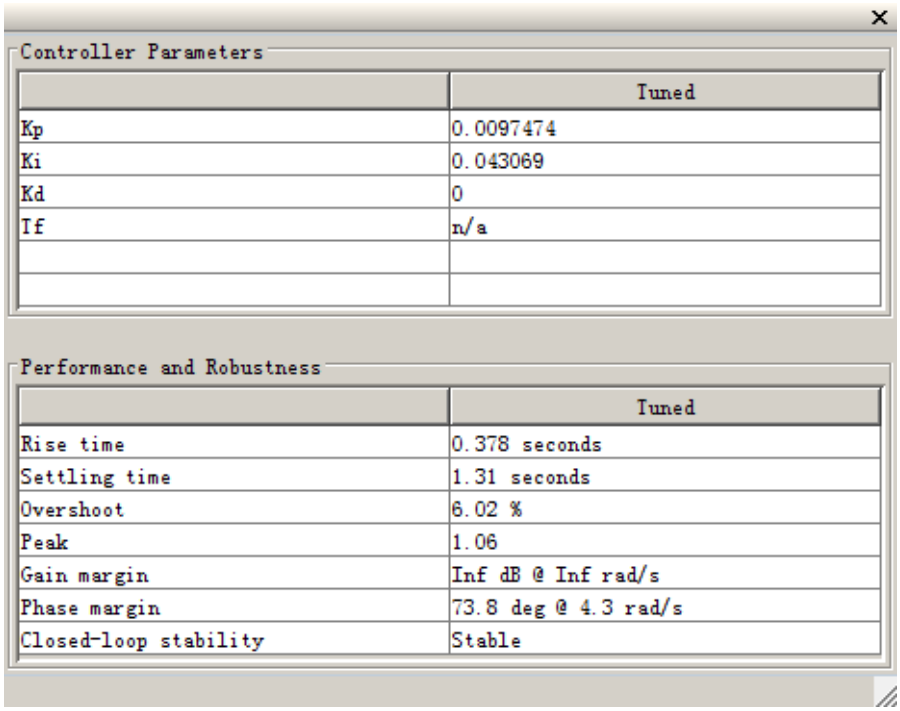


Figure 24 PID view

This is reference tracking of PID view.



Controller Parameters

	Tuned
Kp	0.0097474
Ki	0.043069
Kd	0
Tf	n/a

Performance and Robustness

	Tuned
Rise time	0.378 seconds
Settling time	1.31 seconds
Overshoot	6.02 %
Peak	1.06
Gain margin	Inf dB @ Inf rad/s
Phase margin	73.8 deg @ 4.3 rad/s
Closed-loop stability	Stable

Figure 25 PID parameters

This is the parameters of PID view.

7 Conclusion

The goal of this project was actually redesigning one of the body of NAO, which is a humanoid robot. But when you do a research about something, you should know more about that thing. So doing a general analysis of NAO is very necessary. And after the research, there is no doubt that there is much space for NAO to do the improvement, for example, the motor. According to the research now, in an ideal aspect, it can be move faster and more flexible.

The result shows a lot to us, since we also did many comparison to other robots in the beginning of the research. What NAO lacks is its flexibility and its speed of movements. Or in other words, if it can change its flexibility, maybe it can control its speed, when human control NAO, we can give the command when we need.Which is the other robots have done now.

But what we can do is through simple calculation to give the possibility of the improvements, if it can be make it or not, there is progress. Since it maybe needs more precise calculations and many different methods to prove that, and also it maybe needs to put the possibility into practice. It will be tied with many other aspects, it’s not just a simple calculation about Matlab.

References

[1] Parameters of NAO robot [Online] Chinese; December 2015.

URL: http://wenku.baidu.com/view/3baea732daef5ef7ba0d3cfa.html?from=search

Accessed 14 March 2017.

[2] Nearly 20 robots showing in Shanghai Expo [Online] Chinese Radio Website; June 2010.

URL:http://news.163.com/10/0626/12/6A3RRA5R00014AEE.html.

Accessed 14 March 2017.

[3] Six degrees of freedom [Online] February 2017.

URL: https://en.wikipedia.org/wiki/Six_degrees_of_freedom

Accessed 14 March 2017.

[4] Brief introduction of ASIMO [Online] MiracleSunYuan; June 2010.

URL: http://wenku.baidu.com/view/1d9164fafab069dc502201fa.html?from=search

Accessed 14 March 2017.

[5] Atlas: The most advanced robot [Online] Gezhiwu1213; January 2015.

URL: http://wenku.baidu.com/view/4a85409ab8f67c1cfad6b8e4.html?from=search

Accessed 14 March 2017.

[6] Alpha 1S humanoid robot [Online] Chinaman; June 2015.

URL:http://wenku.baidu.com/view/e7a5547e9e31433238689359.html?from=search

Accessed 14 March 2017.

[7] Function introduction of Pepper robot [Online] Piaoyewuhui; December 2015.

URL:http://wenku.baidu.com/view/240071cfa45177232f60a2d4.html?from=search

Accessed 14 March 2017.

[8] Synchronous motors [Online] June 2016.

URL:https://wenku.baidu.com/view/9e53a9ad2b160b4e767fcfe9.html?from=search

Accessed 14 March 2017.

[9] How does an Alternator Work [Online] Learn Engineering; February 2014.

URL:https://www.youtube.com/watch?v=tiKH48EMgKE&spfreload=10

Accessed 14 March 2017.

[10] The working principle of Alternators [Online] Pcmups; March 2012.

URL:http://wenku.baidu.com/view/e25a341b650e52ea55189825.html?from=search

Accessed 14 March 2017.

[11] Introduction of different kinds of motor [Online] July 2012.

URL:http://wenku.baidu.com/view/602e6d105f0e7cd184253643.html?from=search

Accessed 14 March 2017.

[12] Introduction of Induction motor [Online] Caopingandxin; March 2015.

URL:http://wenku.baidu.com/view/7ef0877b03d8ce2f006623f6.html?from=search

Accessed 14 March 2017.

[13] How does an Induction Motor work [Online] Learn Engineering; July 2013.

URL:https://www.youtube.com/watch?v=LtJoJBUSe28&t=31s

Accessed 14 March 2017.

[14] Basic working principle of single induction motor [Online] Hongzhanlu; July 2016.

URL:http://wenku.baidu.com/view/82e97c8848d7c1c709a14579.html?from=search

Accessed 14 March 2017.

[15] DC Motor, How it works [Online] Learn Engineering; September 2014.

URL:https://www.youtube.com/watch?v=LAtPHANEfQo

Accessed 14 March 2017.

[16] Reprinted from Brushless DC Motor, How it works [Online] Learn Engineering;

October 2014.

URL:https://www.youtube.com/watch?v=bCEiOnuODac

Accessed 14 March 2017.

[17] DC motor [Online] Wangpfq; December 2013.

URL:http://wenku.baidu.com/view/1293bb165901020207409c80.html?from=search

Accessed 14 March 2017.

[18] General introduction of Control theory [Online] Sardine921; February 2012.

URL:http://wenku.baidu.com/view/2b45c2afd1f34693daef3eb5.html?from=search

Accessed 14 March 2017.

[19] Modern Control Theory [Online] Suli; February 2012.

URL:http://wenku.baidu.com/view/8e37f259e87101f69e3195d5.html?from=search

Accessed 14 March 2017.