FORCE-CONTROLLED TRANSCRANIAL MAGNETIC STIMULATION (TMS) ROBOTIC SYSTEM

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ABSTRACT

The use of robots to assist neurologists in Transcranial Magnetic Stimulation (TMS) has the potential to improve the long term outcome of brain stimulation. Although extensive research has been carried out on TMS robotic system, no single study exists which adequately take into account the control of interaction of contact force between the robot and subject's head. Thus, the introduction of force feedback control is considered as a desirable feature, and is particularly important when using an autonomous robot manipulator.

In this study, a force-controlled TMS robotic system has been developed, which consists of a 6 degree of freedom (DOF) articulated robot arm, a force/torque sensor system to measure contact force and real-time PC based control system. A variant of the external force control scheme was successfully implemented to carry out the simultaneous force and position control in real-time. A number of engineering challenges are addressed to develop a viable system for TMS application; simultaneous real-time force and position tracking on subject's head, unknown/varies environment stiffness and motion compensation to counter the force-controlled instability problems, and safe automated robotic system.

Simulation of a single axis force-controlled robotic system has been carried out, which includes a task of maintaining contact on simulated subject's head. The results provide a good agreement with parallel experimental tests, which leads to further improvement to the robot force control. An Adaptive Neuro-Fuzzy Force Controller has been developed to provide stable and robust force control on unknown environment stiffness and motion. The potential of the proposed method has been further illustrated and verified through a comprehensive series of experiments.

This work also lays important foundations for long term related research, particularly in the development of real-time medical robotic system and new techniques of force control mainly for human-robot interaction.

KEY WORDS: Transcranial Magnetic Stimulation, Robotic System, Real-time System, External Force Control Scheme, Adaptive Neuro-Fuzzy Force Controller

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CHAPTER 1

INTRODUCTION

1.1 Background and motivation of the research

Recent developments in the neuroscience area have heightened the need for transcranial magnetic stimulation (TMS) as a non-invasive and powerful method with which to study human brain behaviour. Originally TMS was used in clinical neurology to study motor cortex conduction time and to measure synapses in the brain and spinal cord. Currently, it is being widely used as a research tool to study aspects of human brain physiology including motor function, vision, language and the pathophysiology of brain disorders. TMS has also become an important technique for changing the activity of brain neurons and the functions they sub serve, apart from being a significant adjunct to brain imaging and mapping techniques.

In the TMS procedure, an electromagnetic coil is placed over the head, and a large but brief current pulse is produced and passed through the scalp. The changing magnetic field which this generates induces a current in the conductive tissue of the head including the underlying cerebral cortex. The cortical activity produced by TMS is critically dependent on coil location and orientation. Currently, the coil is positioned manually which can be a problem for precise clinical evaluation and experiments of the TMS technique, where the coil is fixed relative to the head using devices such as face masks, helmets or bite bars which can be uncomfortable for the subject and severely limit experimental duration. In addition, the search for an optimal site to activate the motor cortex has to be carried out by an expert who moves the coil between scalp locations whilst viewing the previous response. Stimulation of other areas is more problematic as no electrophysiological response can be used to indicate correct positioning.

The purpose of this study is to increase the reliability of TMS of the cerebral cortex. This will be achieved by designing and building a robot system which will position and hold the magnetic stimulus coil over a fixed location on the head, at a fixed orientation. The system will be a valuable tool in helping patients who suffer from neurological diseases, such as Parkinson's disease, anxiety disorders, schizophrenia, movement disorders, epilepsy and an alternative treatment for depressions. Transcranial magnetic stimulation is a promising new research field, but more work remains to be done before it can be fully integrated in therapeutic applications in psychiatry and neurology.

1.2 The Research Gaps

Although the TMS technique is very useful, it is not yet widely accepted because of the observed inconsistency of efficiency between subjects. TMS coils produce very dense and defined fields, which mean that a small movement of the coil position leads to a substantial change of the electromagnetic field delivered to a target nerve. It is due to the difficulty to indicate correct positioning with the current available stimulation systems which leads to poor repeatability. This explains the vital need for technologies to support precise navigation and positioning of TMS coils.

Several researchers have developed image-guided TMS to overcome this problem [Herwig et al., 2001; Lancaster et al., 2004; Matthäus et al., 2006a]. By registering MRI data with the patient's head and by tracking the coil, the area of stimulation can be determined easily [Ettinger et al., 1998]. Interleaving TMS and functional brain imaging offers much promise. Matthäus et al. [2006a; 2006b] pointed out a major problem with this kind of technique; exact stimulation is hard to achieve at a pre-defined point, particularly if the site is to be stimulated several times or continuously as in the treatment of depression. Either head movements must be followed by manually adjusting the coil continuously or the head must be fixed. George et al. [1999; 2006b] discusses two problems for combining TMS with functional and structural neuroimaging. One of the limitations with this technique is sometimes it is difficult to match the imaging technique to the temporal duration of TMS. Additional problems have concerned the interference produced by TMS with image acquisition.

A lot of work has been devoted to the development of TMS to assist the neurologist during stimulation sessions. This leads other promising applications of robotics in TMS to position the coil for efficient and reliable TMS procedures. Robot assistance in TMS procedure has been reported by a number of researchers [Matthäus et al., 2006a;

Matthäus et al., 2006b; Finke et al., 2008; Lebosse et al., 2008]. These existing TMS robotic systems, which aim at replacing the hand and the arm of neurologist, are particularly focused on image-guided by means of navigation system to position the coil on subject's head.

Despite its safety and efficacy, current researchers are unable to address the force control as an important feature of the TMS procedure. Most of the research to date has tended to focus on image-guided and navigation system and neglected the study on contact force between the coil and the subject's head which is crucial. Excessive contact force between the coil and subject's head may harm the subject. It is the aim of this study to develop a novel force-controlled robotic system to perform a safe and reliable efficient evaluation of the TMS technique. Apart from providing an indication of TMS system performance, this new robotic system has its emphasis on real-time control, programmability and repeatability which the robot provides to the advantage for TMS. Robotic systems also have much faster response time with reduced computational delay compared to manually TMS procedures, thus allowing faster detection and reaction to the stimulation process.

1.3 Aims and Objectives

This research aims to design and develop a robust and safe force-controlled TMS robotic system to assist neurologists in medical and clinical practice as well as to make stimulation of the cerebral cortex more reliable. This will be achieved by designing and building a robot system which will position and hold the magnetic stimulus coil over a fixed location on the subject's head at a fixed orientation. The robot will track small head movements made by the subject and will maintain a low contact force between the subject's head and coil. One of the major characteristics of this system is to strongly interact with human environment thus many safety requirements are needed, for it to be capable of working in close proximity to a human subject without risk of injury.

The primary aim of this research is to design an appropriate force control scheme and integral safety system to improve the effectiveness of automated TMS robotic system as well as its efficiency and reliability. Both of these systems will be considered with both development in hardware and software, so that it will be capable of working as an integral part of the robotized TMS system.

To achieve the above aim, the following objectives have been set:

- Undertake an in-depth review of the hand-held TMS procedure, medical robotics system, industrial robot and force control schemes.
- Design an intrinsically automated force-controlled Transcranial Magnetic Stimulation (TMS) robotic system.
- Establish a mathematical model of one degree of freedom TMS robotic system to provide an analytical overview of the factors affecting stability of the control system.
- Develop a force/torque sensor data acquisition system to provide a reliable and real-time measurement.
- Design and develop a real-time robotic control system comprising the robot communication, real-time path control, synchronization approach and software process based structure.
- Develop and implement a force control strategy to maintain a light contact force between the coil and subject's head.
- Design and develop an adaptive Neuro-Fuzzy force controller to improved behaviour of the 6 DOF force-controlled TMS robotic system.
- Evaluate the developed force-controlled TMS robotic system via a series of experiments.

This work is conducted in parallel with Xiang Yi [Yi, 2012] who focused on position tracking control. This study represents, for the first time, a detailed investigation and implementation of force control strategy on TMS robotic system with unknown knowledge of the subject's head characteristics, and thereby constitutes an important contribution to the evaluation of the TMS robotic system.

1.4 Hypothesis

An intelligent decision-making method called an adaptive Neuro-Fuzzy control has a possibility to be utilized in TMS robotic system to improve the effectiveness and reliability of TMS procedure in terms of force-controlled approach. The adaptive Neuro-Fuzzy approach has a unique capability of modeling complex nonlinear processes to arbitrary degrees of accuracy, therefore allowing the robotic system to position and hold the stimulating coil at a fixed target position of unconstrained subject’s head.

1.5 Layout of Thesis

Initial work was devoted to the comprehensive review of the TMS procedure, medical robotic system and force control strategies as described in Chapter 2. Prior to the implementation of force control to the TMS robotic system, a TMS procedure analysis was carried out to identify the control functions required to be incorporated in an automated system as discussed in Chapter 3.

From this evolved the detailed design of the TMS robotic system in Chapter 4. A detail explanation of the hardware configuration and software architecture is also discussed. Chapter 5 provides a developed mathematical model of one degree of freedom TMS robotic system. An analytical analysis of the system control performance is conducted and particularly focuses on the factors affecting the control system stability.

Chapter 6 focuses on the implementation of an external force control scheme on the developed 6 DOF TMS robotic system. Initial commissioning test results using a conventional force controller showed the dynamics of the environment to be a significant parameter in the force control stability. This was found problematic in TMS application as subject’s head characteristic is varied from one to another and can be considered as unknown or uncertainties.

As a consequence, an adaptive Neuro-Fuzzy force controller is designed and implemented on the TMS robotic system as discussed in Chapter 7. This is followed by the evaluation of the proposed force-controlled TMS robotic system in Chapter 8. An analysis of test results is also presented. Finally, Chapter 9 presents the conclusions drawn from the study and the recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

This chapter provides an overview of the topics covered throughout the study, begins with an introduction to Transcranial Magnetic Stimulation (TMS), the principle of operation, localization of the coil and requirements for the TMS procedure are briefly described. Secondly, an example of the conventional TMS procedure on motor cortex is discussed together with its drawbacks. The possibility of developing robot assisted systems in TMS is then investigated and relevant existing researches are discussed. Afterwards, the objectives of the proposal to develop force control strategy in TMS procedure are elucidated.

In order to find the most appropriate force control scheme for the TMS robotic system, several force control schemes will be discussed in section 2.6. It is not intended to cover all existing strategies that have been developed, but rather to highlight the aspects and concepts which will be useful for developing a control algorithm for TMS robotic system. A range of force control schemes are classified and compared, followed by a discussion on application of external force control in medical robot systems together with its advantages.

2.1 Introduction to Transcranial Magnetic Stimulation (TMS)

2.1.1 Basic Principle of Magnetic Stimulation

The principles of electromagnetism that underlie TMS were well known more than a century before its introduction by Barker and colleagues 20 years ago [Barker and Jalinous, 1985; Wassermann et al., 2008]. Electrical current can excite cells such as neurons and muscles. The tingling sensation when short-circuiting a low power battery with fingers is a good example of this. Even a strong electrical pulse can be beneficially applied in medicine, for instance, in cardiac defibrillators.

Electromagnetic theory is both elegant and arcane. Magnetic stimulation can “mimic” direct stimulation with electrical current in the tissue. This has beneficial consequences because the magnetic stimulation can reach the tissue without the need for physical contact. Thus, it can be used to examine the brain and treat disorders of the head painlessly and non-invasively. The mechanism of action is similar for both electrical and magnetic stimulation. In order to stimulate neuronal cells, an electric field E must be applied to the tissues; it forces coherent motion of free charges in intra- and extra-cellular spaces [Ruohonen, 2003]. The physical phenomenon behind magnetic stimulation is electromagnetic induction and is governed by a basic law of physics namely, Faraday’s law:

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2-1}$$

In the TMS technique, this relation states that an electric field *E*, and thereby electrical current *I*, is induced in tissue by the time-varying magnetic field *B* from the coil. The solution to the above equation (2-1) gives an estimate of the induced *E* and ignores the effects of the conductivity variations between and within the brain, skull and scalp. Magnetic fields encountered in magnetic stimulation travel freely in air and can easily penetrate through tissue. Therefore, magnetic stimulation can readily reach brain cells even through a high resistance skull. Figure 2-1 below shows the basic principle of TMS.

A magnetic field *B* that induces an electric field *E* is generated by current pulse ***I(t)*** in the coil. The lines of *B* go through the coil and the lines of *E* follow the shape of the coil. The upper-right drawing illustrates two pyramidal axons, together with a typical orientation of the intracranial *E*. The *E*-field affects the transmembrane potential which may lead to local membrane depolarization and firing of the neurons. Events following TMS include: (1) coherent activation of neurons; (2) metabolic and hemodynamic changes; and (3) behavioural changes.

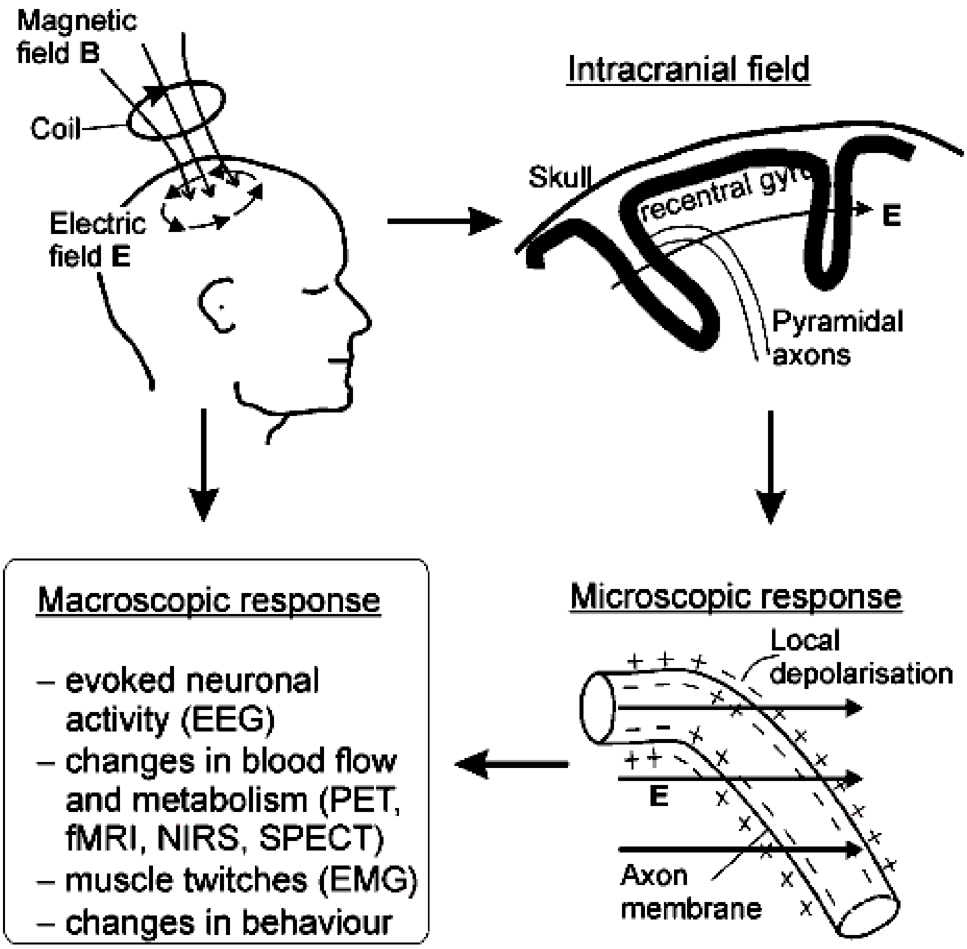

Figure 2-1 Principle of TMS [Ruohonen, 2003]

2.1.2 TMS waveform and current direction

Wassermann et al. [2008] suggest that the effectiveness of TMS in humans is determined by waveform and current direction. Basically there are two pulse configurations of TMS namely single-pulse and paired pulse. For single-pulse TMS, waveform and current direction has been shown to influence motor threshold, motor evoked potential (MEP) latency and silent period duration based on motor cortex and occipital simulations tests [Sommer et al., 2001; Wassermann et al., 2008]. On the other hand, for paired TMS pulses, these factors affect the range of inhibition and facilitation. Nowadays, repetitive TMS (rTMS), capable of delivering a series of high frequency (1-50Hz) pulse is available. This type of pulse produces powerful effects that outlast the period of stimulation. The extent and specificity of the induced motor cortex inhibition and facilitation also depends on TMS waveform and current direction, which enhance clinical efficacy of rTMS. However, rTMS has the potential to cause seizures even in normal individuals. Wassermann et al. [1998] provide safety guidelines describing limits for combinations of frequency, intensity, and train length which should minimize most of the problems.

2.1.3 TMS Coils

The direction of the induced current flow and the size of stimulated area are dependent on the coil shape. There are several available coil types such as circular, figure-of-eight, cap-shaped and conical coils. The field strength from the coil decreases quickly with distance from the coil. The most commonly used type in TMS is the figure-of-eight coil, shown in Figure 2-2(a). This type of coil is more focused and produces strong induced field at the intersection of the two circular coils, compared to a similar sized single coil. Cap-shaped and cone coils are constructed with a pair of circular windings at such an angle with respect to each other that they fit the curvature of the head. These types of coil increase the power at the intersection and are somewhat more effective than the normal planar coils.

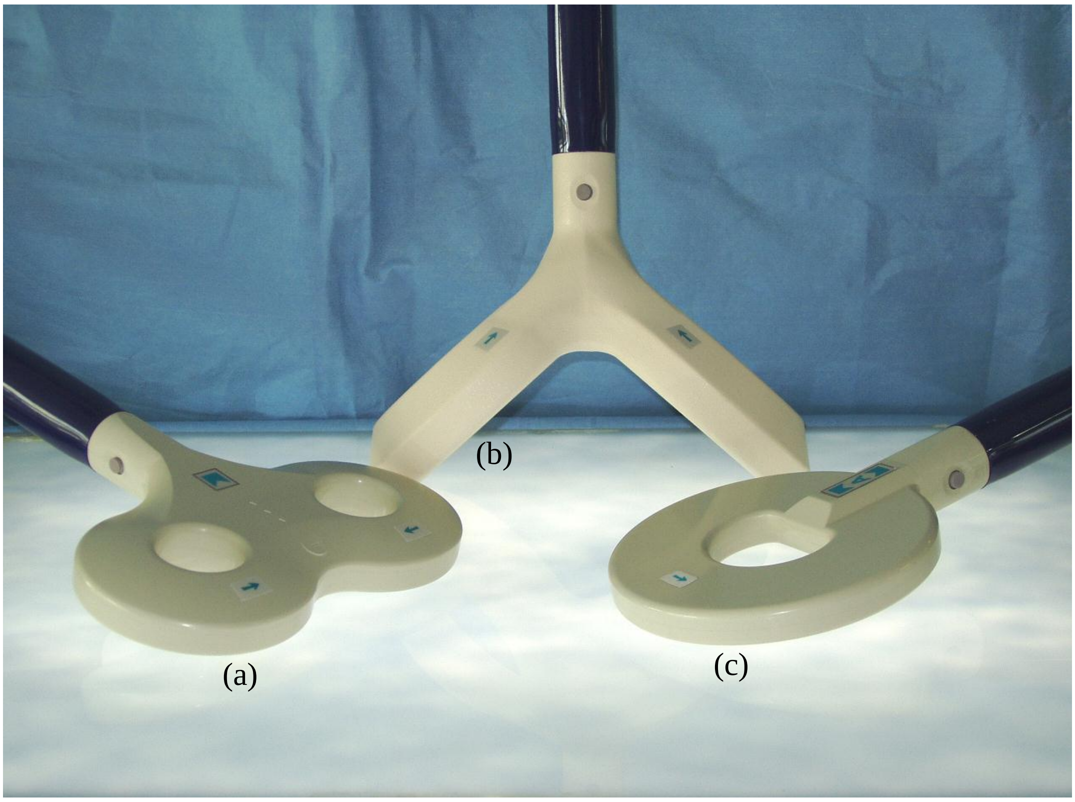

Figure 2-2 TMS coils (a) figure-of-eight, (b) cone-shaped and (c) single shaped coils

2.2 Localization of the TMS Coil

The use of TMS requires knowledge of where on the cortex the magnetic stimulation has to be applied and how it is controlled. Experienced neurologists determine the stimulation site for measuring the latencies of neurons quite easily; the position of the coil over the head is varied until the desired effect is obtained, for example a motor response. This effect defines the optimal stimulation site and this approach is common and practicable. This leads to several localization techniques in the positioning method for TMS, as given in Table 2-1.

Table 2-1 Different method to localize TMS [Herwig et al., 2001]

Principle of localization	**Navigational method**	**Advantage/disadvantage**
Functional	Orientation to motor response, visual phenomenon, speech arrest	Verification by function, not applicable if function is not monitorable (e.g. memory)
Anatomical	10-20-system of EEG, defined landmarks	Standardized, not oriented to individual function or cortex anatomy
Functional and anatomical features combined	5cm anterior to motor cortex in prefrontal cortex	Not oriented to individual cortex anatomy, imprecise within cm
Digitizing devices like 'Polhemus Isotrak'	3D-radio frequency localization and co-registration with MRI	Individual localization, resolution approximately 5mm, not applicable during stimulation
Marker in MRI scan, functional imaging	Marker fixed over stimulated area, combination with PET	Individual localization afterwards, not applicable during stimulation, no monitoring
Stereotactical, mechanically guided navigation	3D stereotaxy by joint sensors in mechanical arms	Individual localization, potentially high precision, monitoring, complex mechanical set up
Stereotactical, optically tracked navigation	3D-camera system, detection of light-emitting diodes, co registration with MRI	Individual localization, resolution approximately 2mm, monitoring during stimulation

A multiple positioning method analysis has revealed that the mechanically guided and optically guided navigation of transcranial magnetic stimulation is a practical and comfortable method for stimulating individually selected cortical areas with high precision. However, with these approaches the head has to be fixed strictly to rule out movements during the stimulation, and it is necessary to combine these methods with functional neuroimaging to make it more reliable.

2.3 Medical and Applications of TMS

Nowadays, there are several non-invasive techniques available in neuroscience research and applications such as EEG/MEG and functional imaging. Each method provides a different view of brain function and one in particular may be the best for a specific condition, however, it is advantageous to obtain multiple views for a more complete understanding. Electroencephalography (EEG) and Magnetoencephalography (MEG) are two techniques used for direct measurements of neuronal activity. EEG measures voltage differences produced by the firing of neurons within the brain between different sites along the scalp. The main application of EEG is in the diagnosis of epilepsy, coma and encephalopathy. However, the main disadvantage of this method is scalp potential can be measured only when a sufficient number of cells are active synchronously. In addition, those that are oriented perpendicular to the surface of cortex have more influence compared to those oriented tangentially. MEG is similar to the EGG but measures intracellular currents. In addition, this technique is a better solution to localize neurons because MEG is not distorted by the skull and scalp. However, MEG is blind to radial sources.

Other functional neuroimaging techniques such as Position Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI) have good spatial localization but less temporal resolution. PET measures regional cerebral blood flow since synaptic activity increases local metabolism and stimulates changes in perfusion. The fMRI is an indirect technique used to measure neuronal activity in which the oxidation state of hemoglobin in the blood is measured. Blood flow increases more than oxygen extraction with metabolism thus, blood becomes more oxygenated.

Several researchers have used different methods to study a similar physiological process to obtain different points of view, for example in a go/no-go experiment [Hallett, 2007].

The go/no-go experiment is a two-choice reaction time experiment to either move or not move depending on the stimulus. From the experimental results, EEG suggests that something is apparently happening despite a negative fMRI where nothing has appeared. A study using TMS clarifies the confusion. The TMS technique detects inhibition as well as increased excitability in the motor cortex. In a case study by Hallett [2007], the EEG detected what happened throughout its time course whereas neuroimaging did not show any activity, as inhibition is not as demanding a metabolism process as is excitation [Hallett, 2007]. Thus, it can be concluded that TMS can be used in conjunction with the other imaging techniques to improve better understanding particularly in neuroscience research.

TMS studies have also played a useful role in the application of pathophysiology, which is a medical branch used to study functional changes associated with or resulting from diseases. For example, TMS can provide information about different mechanisms for genesis of epileptic seizures and for the modes of action of antiepileptic drugs by assessing cortical excitability. In addition, TMS also can potentially be used to quantify physiological effects in individual patients, and this may be more valuable in some circumstances than anticonvulsant blood levels. Cantello [2002] claims studies with TMS have revealed abnormalities in movement disorders such as Parkinson’s disease, Huntington’s disease and dystonia.

TMS stimulation has been applied to change sypnatic strength to obtain long-lasting influences on the brain, for instance by alterations in dendrite spines. Such logic can be used in therapeutic applications for many neurological disorders such as Parkinson’s diseases, dystonia, stroke and epilepsy. TMS can speed up the reaction time in patients with Parkinson’s disease as well as increasing intracortical inhibition in dystonia. The most extensive use of TMS therapy is for psychiatric conditions, mainly depression in which TMS can deliver equally effective focal therapy more easily and with fewer side effects[Wassermann et al., 2008].

As a conclusion, TMS can be suggested as an excellent non-invasive physiological and therapeutic tool and complements other methods to study physiology, motor and sensory area of human brain. Hallett [2007] suggests TMS can add more power to the clinical neurophysiologist for diagnosis and therapy of neurological disorders.

2.4 Conventional TMS Procedure

The typical TMS procedure is given below as an example. Conventionally, subjects are seated in a comfortable chair with their hands placed on their lap. A TMS coil is placed on the scalp and a brief electrical current is passed through the coil, creating a magnetic pulse that stimulates the outer part of the brain, called the cortex. This may cause twitching of a particular muscle in the hand or arm, depending on the location of the coil relative to the position of the motor cortex, i.e part of the brain to control movement. The procedures may be different depending on the subjects, operators, types of illness and their treatments. The procedure may last for two-three hours for every session. The following section will discuss the clinical procedure requirements to ensure a good outcome of TMS.

2.4.1 Clinical procedure requirement and components

In order to implement TMS technology into a clinical practice and usable configuration, it is essential to consider appropriate and additional features into TMS clinical system to achieve a consistent therapy. In particular, unique and proper procedural aspects of a specific therapy (for example, treating depression) are considered as indicated in Figure 2-3 [Wassermann et al., 2008]. Four fundamental aspects of a TMS stimulator system intended for routine clinical use are listed below:

- Patient positioning and comfort
- Accurate and repeatable coil positioning over the course of many treatment sessions
- Management and analysis of patient data to perceive trends and response
- Incorporation of features to monitor the quality of stimulator operation

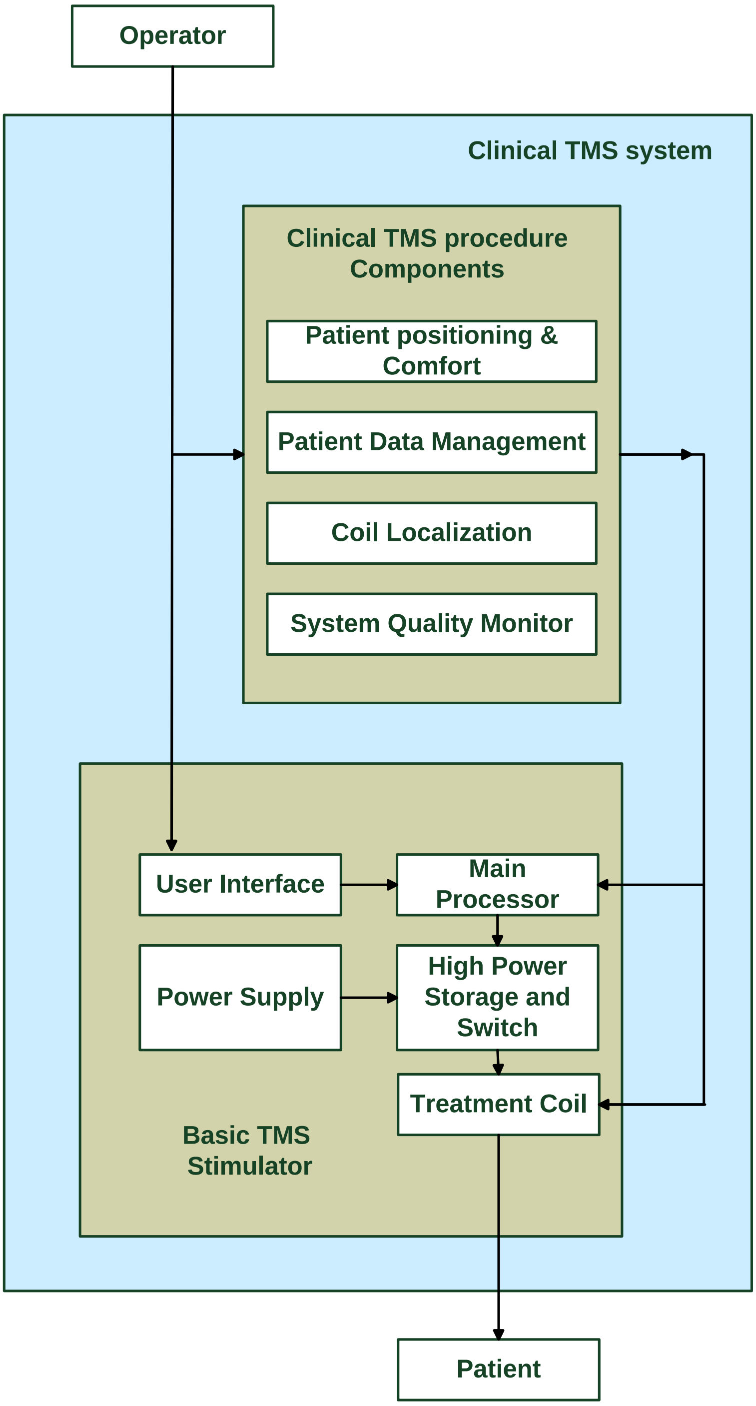

Figure 2-3 Clinical TMS System [Wassermann et al., 2008]

Patient comfort features are important to improve tolerability, to minimize disruptions and undesired movement of the subject relative to the coil as a typical session of treatment may take 10-30 minutes. The clinical system should also provide the clinician with a straightforward means of locating the motor threshold position and navigating from the position to the treatment position [Wassermann et al., 2008]. Several approaches such as markers, swim cap, mechanical alignment and image guided graphical methods have been implemented in order to provide reference points for coil placement. However, all previously mentioned approaches carry various well known limitations that include being uncomfortable for patients, and the three-dimensional image set may limit the clinical practice routine. Optical and ultrasonic coordinate measuring systems offer accurate methods for repeatable coil positioning but cost may prohibit adoption of this kind of technology in typical TMS clinical practice.

It has been suggested that the positioning method and apparatus should be intuitive, repeatable, accurate, comfortable and acceptable to the patients, for example by minimizing restraint and hair disruption. Furthermore, the capability of supporting the coil mass and maintaining its position throughout a prolonged TMS procedure will be necessary without excessively constraining the patient. A contact sensing feature such as force sensor that provides real-time feedback to the operator should be incorporated since the magnetic field diminishes rapidly with distance from the coil. Other data management features must also be incorporated into the TMS clinical system to assist the operator to recall treatment protocols, review patient treatment history, record observations as well as to analyze trends [Wassermann et al., 2008].

2.5 Current research in TMS Robot Assisted Systems

Robot assistance in TMS procedure has been reported by a number of researchers [Matthäus et al., 2006a; Matthäus et al., 2006b; Finke et al., 2008; Lebosse et al., 2008]. These existing TMS robotic systems aimed at replacing the hand and the arm of neurologist are particularly focused on image-guided systems by means of navigation to position the coil on subject head.

2.5.1 A robotic image-guided Transcranial Magnetic Stimulation

Lebosse et al. [2008] propose a new image-guided robotic TMS system that used a seven degree of freedom redundant manipulator arm. The robotic system consists of three subsystems which are a spherical mechanism, an actuated prismatic joint and a spherical serial wrist. The first subsystem deals with the three degree of freedom serial structure (J1, J2 and J3) which is used to provide kinematic positioning. The orientation of the coil around a sphere centered on the subjects head can be achieved using a spherical workspace. J4 which is an actuated prismatic joint is used to control the coil/head including a force sensor that is attached to the coil casing. A hybrid position/force control scheme with a vision-based head position localization system will be implemented. The spherical serial wrists are used to maintain the coil position so it is always tangent to the head surface without changing it centre position. The remaining joint is controlled to follow the cortical column direction. Figure 2-4 presents the kinematics scheme and the CAD model of the robot.

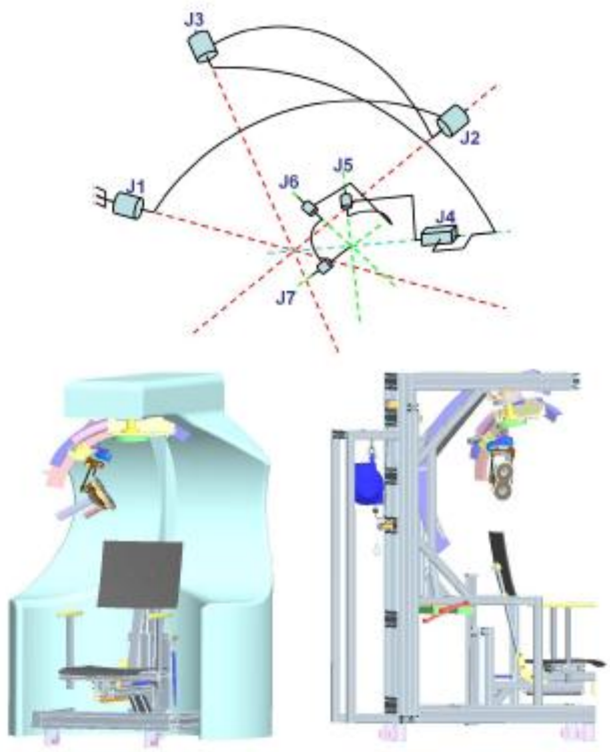

Figure 2-4 The kinematics scheme and the CAD model of the robot [Lebosse et al., 2008]

However, the proposed system has some drawbacks. One question that needs to be addressed is the reliability of the redundant mechanism, which provides the manipulator with dexterity and versatility in its motion. There is also no discussion about hybrid position/force control implementation in which this research fails to take force control into account. To date, to the knowledge of the author, there has been no research on force control implementation on TMS robotic system.

2.5.2 A robotized TMS for motion navigated brain stimulation and brain mapping

Matthäus et al. [2006b] and Finke et al. [2008] propose a robotic TMS system for motion compensated navigated brain stimulation and brain mapping system. Their system comprises six main components which are the circular coil, Adept Viper s850 robot, PC (2.8GHz), Polaris tracking system, robot controller and headband as shown in Figure 2-5**.**

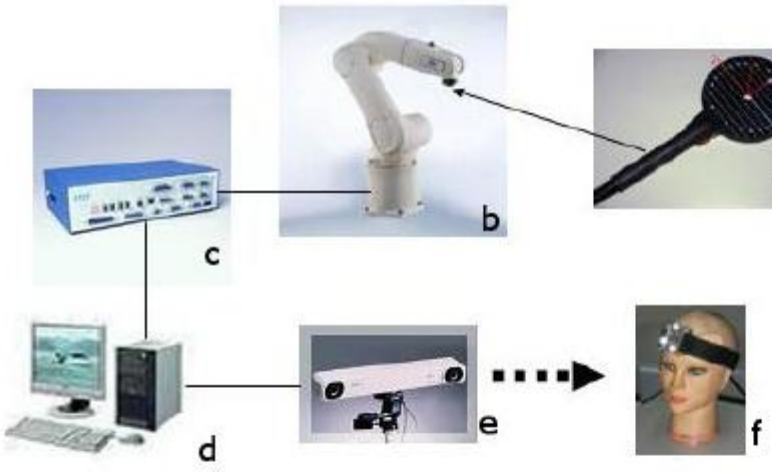

Figure 2-5 The six main components for robot-guided TMS: (a) TMS coil, (b) Adept robot, (c) robot controller, (d) computer, (e) Polaris tracking system, (f) headband [Finke et al., 2008]

Figure 2-6 Application set up. The patient's head is tracked by a POLARIS camera (not visible) enabling the robot to compensate for head movements [Matthäus et al., 2006b]

During stimulation, the MRI image data is used to reconstruct the head position and using this information the coil target position is defined. This position is then transformed to robot coordinates using the Polaris tracking system and pre-establish registration. Figure 2-6 shows the application set up of the robot guided TMS system.

During the TMS procedure, a 3D MRI data set is used to create a virtual head model. Then, the virtual world is registered with the real world using the Polaris system. Once the head tracking system establishes a link between the virtual space and the robot workspace, the robot will position the TMS coil according to the path planning and the operator will pick a target point on the subject’s head and also the desired distance and orientation of the coil from the head. Nevertheless, approaches of this kind carry with them various well known limitations. The main weakness of the study is the failure to address how the distance between coil and subject’s are defined. Consequently, overlooks the fact to quantify the contact force during the procedure. This brings a safety concern if the robot attempts to apply a large force to the subject. Another major source of uncertainty in the study is the system does not take the different coil characteristics into account and the cost of MRI scan as it is necessary to perform the scan for each subject and before the treatment.

Most studies have consistently failed to address the force control as an important feature of the TMS procedure. Most of the research to date has tended to focus on image-guided and navigation system and neglected the study on contact force between the coil and the subject’s head which is crucial. It was considered the force control would usefully improve and extend the TMS robotic system. The next section will discuss several force control strategies in order to find the most appropriate force control scheme for the TMS robotic system.

2.6 Review of Force Control Strategies

Robot manipulator arms have been used in industry for many years to perform a variety of tasks involving interaction with their environment in areas such as in manufacturing (assembly, deburring, cutting, polishing and handling parts) and also more recently in non-industrial environment (hospital, welfare, service, maintenance and space) [Werbos, 1974; Pierrot et al., 1999; Poignet et al., 2003]. Implementation of these tasks require a robot to satisfy the specified position trajectory and control the necessary interaction force to either overcome the resistance from the environment or comply with the environment.

In order to achieve successful execution of a number of motions where the robot end effector has to manipulate an object or perform some operation on a surface, control of the interaction between the robot manipulator and its environment is crucial. In a constrained motion, the environment sets constraints on the geometric paths that can be followed by the end-effector. In such a case, the use of a purely position control strategy is not possible unless the tool trajectory is planned extremely accurately and the control ensures a perfect monitoring on this trajectory. The control strategy requires an accurate model of both the robot manipulator (kinematics and dynamics) and the environment (geometry and mechanical features). Manipulator modelling can be known with enough precision, however a detailed description of the environment is difficult to obtain.

In practice, consider an example of a manipulator washing a window with a sponge. The compliance of the sponge may possibly regulate force applied to the window by controlling the position of the end-effector relative to the glass. This approach would work very well if the position of the glass is known very accurately or the sponge is very compliant. However, it is significantly difficult to perform operations in which the manipulator presses against a surface if the stiffness of the end-effector, tool and/or environment is high. If there is uncertainty in the position of the glass or any error in position control, this would ultimately lead to breakage of the glass. This drawback can be overcome by specifying a contact force that is to be maintained normal to the surface. It can be suggested that an enhacement of interaction control performance can be achieved by providing force measurements by mounting the force/torque sensor on a robot manipulator, typically between the wrist and the end-effector and its reading is passed to the robot control unit via a suitable interface [Raibert and Craig, 1981; Burn et al., 2003]. This enhancement is in the form of an outer feedback loop employing compliance or force controller that encloses the inner Cartesian position control system and will be discussed in detail in the following section.

In addition, robot force control involves integration of task goals such as modelling of the environment, position, velocity, and force feedback and adjustment of the applied torque to the robot joints. Zeng et al. [1997] conclude that feedback of various measurement signals of the output of a robot such as position, velocity, force and the selection of command input signals to a robot result in different force control methods.

2.7 Fundamental of Force Control Schemes

When a robot is moving freely along a trajectory, position control alone is able to achieve the desired motion. However, force control will have to be applied if the task involves any contact between the robot end-effector and the environment. The force control application offers enhancement to the effectiveness of position control. Dombre and Khalil [2007] suggests that robot force control algorithms can be divided into several methods:

- involving the relation between position and applied force – active stiffness control;
- using the relation between velocity and applied force – impedance control;
- using position and force feedback - parallel hybrid position/force control and external force control;
- using force feedback – explicit force control;

The following sections will discuss these control methods in details.

2.7.1 Active stiffness control

Salisbury [1980] proposed a method to control the apparent stiffness of a manipulator called *active stiffness control*. In this approach the robot is considered as a programmable spring, where the compliant behaviour of the manipulator can be controlled by changing stiffnesses under program control to achieve varying task requirements. This allows the programmer to specify the three translational and three rotational stiffness of a frame located arbitrarily in task space coordinates.

Figure 2-7 illustrates the block diagram of active stiffness control. For a better understanding this control scheme can be divided into two parts, namely the controller and the basic dynamic system.

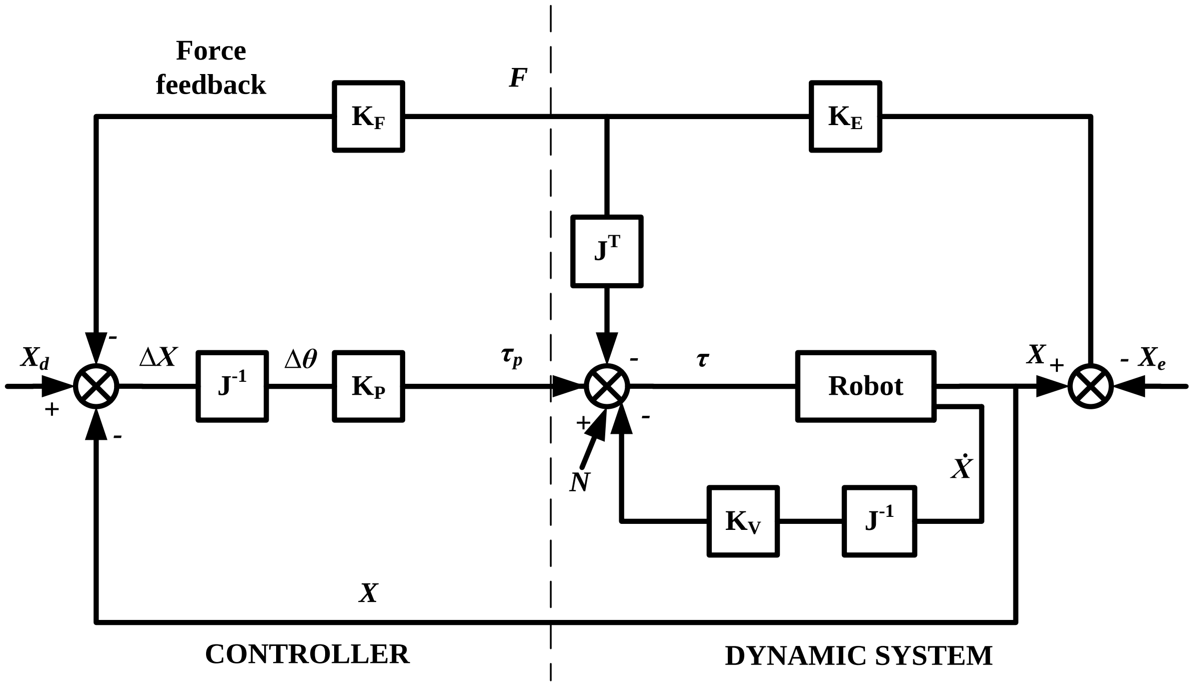

Figure 2-7 Active Stiffness Control scheme

where the variables can be defined as listed;

J	Jacobian matrix
X_d	the desired position in task space
X	Position in the task space
$\dot{X}$	Velocity in the task space
ΔX	Position error
$\Delta\theta$	Joint angle displacement
τ_p	Joint torque
N	Feedforward compensation for gravity, centrifugal and Corialis forces
X_e	Position of the contact environment
K_E	Stiffness of the sensor and environment
K_p	Joint stiffness matrix
K_F	Compliance matrix
K_v	Velocity damping matrix
F	Contact force

The basic dynamic system comprises a robot and its environment as well as velocity feedback and nonlinear compensation for linearizing the robot dynamic system. The basic stiffness formulation ($F=K\Delta X$) is applied for the stiffness control loop implementation, where K is the Cartesian stiffness matrix. Using the Jacobian matrix differential transform, the Cartesian displacement ΔX is determined from the joint angle displacement $\Delta\theta$ in the form of

$$\Delta X = \mathrm{J}\,\Delta\theta \tag{2-2}$$

Assuming that the friction and dynamic forces are compensated or are small enough to be neglected, the joint torque τ that is necessary to apply the contact force is computed using

$$\tau = \mathrm{J}^{\mathrm{T}} F = \mathrm{J}^{\mathrm{T}}\,\mathrm{K}\,\Delta X \tag{2-3}$$

Combining equations (2-2) and (2-3),

$$\tau = \mathrm{J}^{\mathrm{T}}\,\mathrm{K}\,\mathrm{J}\,\Delta\theta = \mathrm{K_p}\,\Delta\theta \tag{2-4}$$

Thus, the commanded joint torque τ_p due to the contact force is defined as follows

$$\tau_p = \mathrm{K_p}\,\Delta\theta \tag{2-5}$$

where K_p is the (6x6) joint stiffness matrix. This approach allows the user to specify mechanical stiffness of the manipulator by varying the value of K_p which determines the proportional gains of the stiffness control loop in the joint space. This makes the robot stiff along the axis under position control so that it can follow the desired position trajectory as close as possible, while a low gain is set to force controlled directions to prevent excessive build up of contact force. One of the limitation of this control scheme is the control can be lost at singularities since the Cartesian stiffness matrix is transformed using Jacobian [Kiguchi and Fukuda, 1999].

2.7.2 Impedance control

According to Hogan [Hogan, 1985a; Hogan, 1985b], the fundamental philosophy of impedance control is that the manipulator control system should be designed not to track a motion trajectory alone but rather to regulate the mechanical impedance Z_m of the manipulator, as defined by the relationship between the velocity $\dot{X}$ and the applied force *F*. In the frequency domain, this is represented by

$$\frac{F(s)}{\dot{X}(s)} = Z_m(s) \tag{2-6}$$

In terms of position *X(s)*, the equation is

$$\frac{F(s)}{X(s)} = sZ_m(s) \tag{2-7}$$

In general, the robot is equivalent to a second order mass-spring-damper system, with transfer function;

$$sZ(s) = Ms^2 + Cs + K \tag{2-8}$$

where *M*, *C* and *K* represent the desired inertia, damping and stiffness matrices respectively. There are two ways to implement the impedance control behaviour which are depending on the need of an external force measurement [Dombre and Khalil, 2007] as shown in the Figure 2-8 and Figure 2-9;

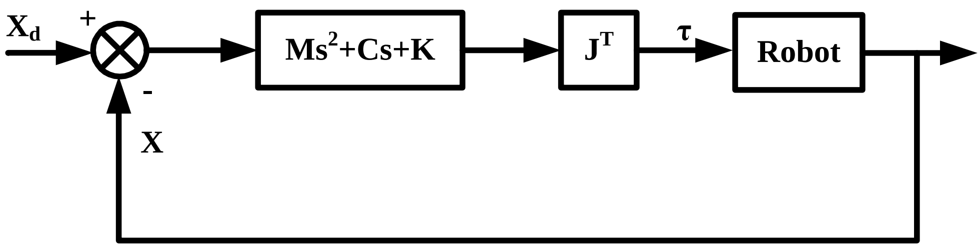

Figure 2-8 Impedance control scheme without force feedback

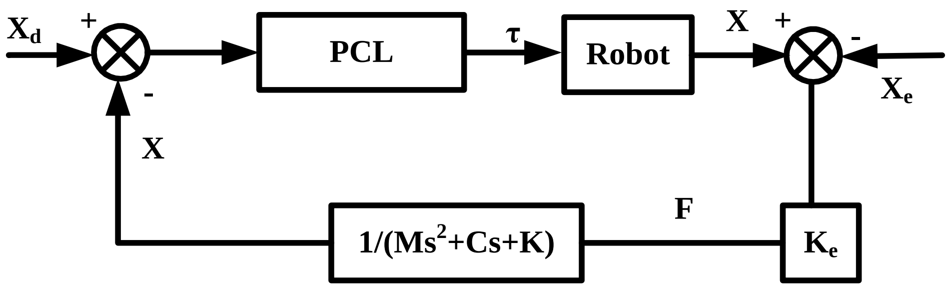

Figure 2-9 Impedance control scheme with force feedback (PCL: position control loop)

Figure 2-8 illustrates an implementation of the impedance control strategy without force feedback or so called implicit force control. The dynamics of the robot is neglected except for the gravity compensation Q. In this case, the control law is given by;

$$\tau = J^T[B(\dot{X}_d - \dot{X}) + K(X_d - X)]\dot{\mathrm{X}} + Q \qquad (2\text{-}9)$$

The *K* and *C* matrices are equivalent with the proportional and derivative gains in the task space (PD control) which can be represented as the stiffness matrix and the damping matrix of the robot respectively. This type of control is suitable during robot small motions for example in mechanical parts insertion task.

The second method can be derived from the dynamic robot model in the joint space which yields the following equation

$$\tau = M(q)\ddot{q} + H(q, \dot{q}) + J^T F \qquad (2\text{-}10)$$

where *M* is the inertia matrix of the robot, and *H* contains the Coriolis, centrifugal and gravity forces/torques. By expressing the vector $\ddot{X} = J\ddot{q} + \dot{J}\dot{q}$ with joint variables in equation (2-10) yields to

$$\tau = M(q)J^{-1}[\ddot{X} + \dot{J}\dot{q}] + H(q, \dot{q}) + J^T F \qquad (2\text{-}11)$$

then replacing the vector $\ddot{X}$ as expressing in the following equation;

$$\ddot{X} = \ddot{X}_d + M^{-1}[B(\dot{X}_d - \dot{X}) + K(X_d - X) - F] \qquad (2\text{-}12)$$

which leads to

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