**A TECHNICAL REPORT**

**ON**

**STUDENTS’ INDUSTRIAL WORK EXPERIENCE**

**SCHEME (SIWES)**

**HELD AT**

**APPLIED ARTIFICIAL INTELLIGENCE AND ROBOTICS LABORATORY**

**BY**

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**EEG/2016/054**

**SUBMITTED TO:**

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**DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING**

**FACULTY OF TECHNOLOGY**

**OBAFEMI AWOLOWO UNIVERSITY,**

**ILE-IFE, OSUN STATE.**

**IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE**

**AWARD OF BACHELOR OF SCIENCE DEGREE IN**

**ELCTRONIC AND ELECTRICAL ENGINEERING TECHNOLOGY**

**JAN, 2022.**

Department of Electronic and Electrical

Engineering,

Obafemi Awolowo University,

Ile-Ife, Osun State.

1st August, 2021.

The SIWES Coordinator,

Department of Electronic and Electrical Engineering,

Obafemi Awolowo University,

Ile-Ife, Osun Sate.

Dear Sir,

**LETTER OF TRANSMITTAL**

In partial fulfillment for the requirement of the award of B.Sc. (Hons.) in Electronic and Electrical Engineering, I, OLATEJU Emmanuel Oluwasegun hereby submit for grading, the report of the Students’ Industrial Work Experience Scheme (SIWES) – EEE400 which was undertaken at Applied Artificial Intelligence and Robotics Laboratory, Obafemi Awolowo University, Ile-Ife, Osun State.

Yours faithfully

………………………………….

**OLATEJU Emmanuel Oluwasegun**

**EEG/2016/054**

**CERTIFICATION**

This is to certify that I, OLATEJU Emmanuel Oluwasegun, with matric number EEG/2016/054, carried out the Students’ industrial Work Experience Scheme (SIWES) programme under my supervision and submit this report for grading and that the contents of the report were written and compiled by him with respect to the skills acquired during the course of the programme.

……………………… …………………….

Dr. F.K. Ariyo Date

SIWES Coordinator

**DEDICATION**

I dedicate the period of the work experience scheme to God almighty my parents, my industry based supervisor and colleagues.

Most importantly, I dedicate the works done during the work experience scheme to my industry based supervisor, the person of Dr. K.P Ayodele and other colleagues who provided career and moral mentor-ship to me during and after the period of the work work experience scheme.

**ACKNOLEDEMENT**

I give thanks to God Almighty, who thought of me as worthy of holding on to his breath of life.

I sincerely appreciate my mother, MRS. F.O Olateju who despite all odds gave me the rare chance of being educated and who despite needing my presence during the period of the work experience scheme understood my desires and needs, thus allowing me to be physically distant from her for the period of the work experience scheme.

My sincere appreciation also goes to my industry based supervisor, Dr. K.P. Ayodele for his consistent mentoring and guidance, not just in technical areas and career-wise, but also in areas of moral-development and handling of personal matters.

With every drop of gratitude in my heart , I appreciate Mr. Segun Akinniyi and all other staffs of Applied Artificial Intelligence and Robotics Laboratory for their continued support and trusting in my abilities enough to leave certain issues into my care.

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**LIST OF ABBREVIATIONS**

**BCI:** Brain Computer Interfacing

**BLDC:** Brush-less Direct Current

**CSP:** Common Spatial Patterns

**EEG:** Electroencephalography

**EPs:** Evoked potentials

**ERD:** Event related desynchronization

**ERPs:** Event related potentials

**ERS:** Even related synchronization

**ESC:** Electronic Speed Controller

**FBCSP:** Filter banks common spatial patterns

**fMRI:** Functional Magnetic Resonance Imaging

**fNIR:** Functional Near Infrared Imaging

**FES:** Functional Electrical Stimulation

**MOSFET:** Metallic Oxide Semiconductor Field Effect Transistor

**PET:** Positron Emission Tomography

**PULSR:** Platform for Upper Limb Stroke Rehabilitation

**PWM:** Pulse Width Modulation

**MEG:** Magnetoencephalography

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**ABSTRACT**

Brain Computer Interfacing(BCI) is a developing and inter-disciplinary field that deals with the extraction of intelligence of human-activity from the human brain as signals, using either invasive or non-invasive methods and the interpretation of these signals to their equivalent associated human-activity using intelligent processing methods from computer-science, electronic-engineering and mathematics.

PULSR which stands for Platform for Upper-Limbs Stroke Rehabilitation is a two degrees of freedom robot designed to employ controlled physical exercise with feedback from Brain Computer Interfacing and machine-learning systems in the rehabilitation process of early stage stroke patients having their upper-limbs inactive due to the stroke condition.

A brush-less direct current(BLDC) motor is a three-phase coil(star sconfiguration) motor making use of the three-phase coiled electromagnets as its stator, a set of permanent magnets as its rotor part and hall sensors for generation of rotor position and next control-signal information, unlike the traditional servo motor which requires no information on rotor position and does not have transient states(changing control-signal). The special configuration of a BLDC motor thus makes it require the use of a smart controller generally called an Electronic Speed Controller(ESC).

**CHAPTER TWO**

**LITERATURE REVIEW**

**2.1 BRAIN COMPUTER INTERFACING(BCI)**

Brain Computer Interfacing is a developing field of study that inquires ways to map various forms of signals of the brain, and optionally signals from other parts of the body(eye, muscle, e.t.c.) to intelligent activity of the human body, as all activities and experiences of the human body are either pre-processed or post-processed by the brain for generation of interpretation or instruction for another set of activity.

The ability of BCI to map signals of the brain along with signals from other parts of the body to intelligent activity makes it a very important area of study in so many industries ranging from the medical-rehabilitation industry to the gaming industry, government intelligence and investigation agencies make use of BCI systems among many other industries. BCI systems can be used in lie detection, anomaly behaviour monitoring, control of prosthetic hands or legs, interpretation and then conversion of intended human-movement or activity to game control signals and so much more.

BCI applications can be divided into three classes based on the preferred state of user in development and usage. There is the passive BCI, active BCI and reactive BCI. In the passive BCI, the idle state or the state where the user is engaged in some cognitive task without intentions of controlling the BCI system is of interest. In active BCI, the activity of interest has to be properly specified through some predefined cues. The users goal is to control the BCI system. The activity of interest which is some predefined cognitive task can be movement of specific parts of the body or being engaged in a mentally tasking exercise such as mathematical computations or artistic development. In a reactive BCI, the activity of interest is the brains response to external stimulus, the stimulus being visual, auditory,sensual or a combination.

A typical BCI system consists of four stages with an optional user or supervisor feedback system.

1. The signal-acquisition block:

The signals from the brain can be acquired by invasive or non-invasive methods. The non-invasive methods are generally preferred over the invasive methods as they require less protocols and supervision to be used, though the invasive methods give signals with better time and spatial resolution. There are majorly five non-invasive technologies used in acquiring the brain signals used in BCI systems.

1. Electroencephalography(EEG)
2. Functional Magnetic Resonance Imaging(fMRI)
3. Functional Near Infrared Imaging(fNIR)
4. Magnetoencephalography(MEG)
5. Positron Emission Tomography(PET)

The EEG method is usually preferred over others due to its low-cost compared to other technologies and being available and accessible as needed. EEG records electrical activity on the cortex of the brain(brain surface) by placing a group of electrodes, either wet or dry electrodes on the scalp. The arrangement of neurons in the cerebral cortex and its proximity to the skull favor recording by EEG. It is common knowledge in BCI (Rajesh, 2013) that the spatial resolution of EEG is typically poor (in the square centimeter range) but the temporal resolution is good (in the milliseconds range). The recorded signals are called EEG signals and are multi-space time-series of voltages in the micro-volts range. During the recording of EEG data in a BCI development exercise, labels of user activity are attached to time windows of user(subject) activity and are commonly called markers or event-markers. Thus, the EEG data is stored as 3D matrix of space, time and event-marker.

In the placement of the EEG sensors, a defined scalp mapping system called the 10-20 electrode placement system has to be followed precisely. Also, impedance between the scalp and the sensor has to be measured to be within the range defined by EEG device manufacturer for acquisition of meaningful data.

The EEG recording is a summation of spontaneous-EEG which encodes human-activity information and background-EEG which is majorly noise also called artifacts and contains little or no information on neural-state or human-activity. The artifacts can be generated by movement of certain body parts or can be from external electrical devices, for this reason BCI users are usually advised not to move during a BCI development exercise and well detailed and instructive protocols are employed during BCI experiments. These artifacts need to be removed using algorithms or filters depending on the application so as to effectively decode EEG data.

1. The Signal Preprocessing block:

Signal preprocessing requirement varies depending on the technology used in acquiring the brain signals. In cases where the brain signals are acquired using EEG technology, Rajesh P.N. RAO(2013) states that the weak amplitude of the EEG signal makes it highly susceptible to noise contamination called artifacts from other parts of the body and from nearby electrical devices.

The presence of EEG artifact from external electrical devices can be reduced by making use of a 60Hz notch-filter for removal of power-line interference due to instrumentation. Also a 1Hz to 30Hz band-pass filter is traditionally used with EEG signals as EEG information carrying signals rest within this range of frequency. The band-pass filtering helps separate information bearing EEG signal from background EEG signal bearing artifacts and other forms of unwanted noise.

Artifacts due to changes in body parts are quite difficult to remove as they are not easily distinguishable from meaningful EEG data. Artifacts due to eye-movements are called ocular-artifacts and those due to movements of other body parts are called muscular-artifacts. There exists powerful algorithms for the removal of body artifacts from EEG data, but depending on application the body artifacts can be considered useful information. In cases where we wish to also detect movement of the eye, ocular-artifacts in EEG data due to eye-blinking are no longer considered as artifacts. Thus signal-preprocessing approach varies according to BCI application and signal-acquisition technology employed.

After successful separation of meaningful EEG data from artifacts, the EEG signals may need to be scaled depending on the requirements of successive blocks in the BCI system and also mapped to human/neural-activity. The method of scaling adopted also depends on the requirement of successive blocks in the BCI system. The min-max scaling method or the centralization method can be adopted as required for successive blocks.

1. The Features Extraction block:

In order to map EEG signal to neural-activity, variables indicating such neural-activity need be computed from the preprocessed EEG signals around the time window of interest. This is done by extracting the time-window of interest around the time-frame indicated by the event-marker in the EEG signal, this is called epoching. The resulting EEG signals are called epochs and are the multi-space time-series from which variables indicative of neural activity are computed.

The variables computed can be in the time-domain, frequency-domain or a combination of both. Since the epochs are multi-space time-series data there exists time-domain analysis methods, frequency-domain analysis methods and also spatial filtering methods for computing variables that give information on neural activity also called features.

Depending on the activity of interest and its commonly associated brain signal elicitation, the feature extraction method is chosen. These common brain signal elicitation's associated with certain neural-state activity are generally referred to as event-related-potentials(ERPs) or evoked-potentials(EPs). A common class of event-related-potentials are event-related-desynchronization(ERDs) and event-related-synchronizations(ERSs) which are commonly associated with cognitive functions involving motion and imagination of motion called motor-imagery and are largely observed in the frequency domain. There is also the P300 and P100 signals which are positive deflections in the EEG signals that occur around 300ms and 100ms respectively after the occurrence of some target stimulus which can be single or a combination of visual, auditory or tactile stimuli. A common class of evoked-potentials is the steady state evoked potential(SSVEP) which occurs in response to steadily changing visual patterns as electrical activity in EEG signals of frequency similar to the frequency of the visual pattern.

Fourier transforms and wavelet transforms are frequency analysis methods commonly used for extracting frequency-domain features such as those indicative of ERDs and ERSs in motor-imagery experiments. The wavelet transform is preferred due to its trade-off balance between time-domain resolution and frequency-domain resolution. Hjorth parameters and auto-regressive modelling are time-analysis methods among others used for time-domain features extraction. There exists spatial filters for feature extraction among which common spatial patterns(CSP) and the filter banks common spatial patterns(FBCSP) are more prominent as they produce better classification results on EEG data.

1. Classification:

After extraction of features from the EEG data, a function that maps the feature vector to neural-activity is required. This function can be called a prediction function or as commonly called a (machine-learning)classifier. This function is developed by a common machine-learning technique called supervised-learning in which, the features are passes to the machine-learning system along with the event-markers as labels.

**2.1.1 Areas of Application of Brain Computer Interfacing**

A BCI system is also a communication system between the brain and external devices, making it possible for brain signals to be translated into control commands for external devices. This feature of BCI systems makes it useful in replacement of physically disabled body-parts, by controlling prosthetic parts using the brain alone. The communication and control capabilities of BCI makes it applicable in various areas and in recent times BCI systems have been validated for use in noisy structured environments such as homes and hospitals resulting in the BCI systems gaining popularity among regular people. In the last years, some research efforts have been done on its use about smart environments,smart control systems, fast and smooth movement of robotic arm prototypes, motion planning of autonomous or semi-autonomous wheelchairs, as well as controlling orthoses and prostheses. A number of research endeavors confirmed that different devices such as a wheelchair or robot arm can already be controlled by a BCI device.

1. Applications to unmanned aerial vehicle:

LaFleur *et al,*(2013) gained extensive media attention for demonstrating the potential of noninvasive EEG-based BCI systems in 3D control of a quadcopter. Five subjects were trained to modulate their sensorimotor rhythms to control an AR drone navigating a physical space using an obstacle course. Visual feedback was provided through a first person view camera attached to the drone. The subjects were able to quickly pursue a series of foam ring targets by passing through them in a real-world environment. They obtained up to 90.5% of all valid targets through the course, and the movement was performed in an accurate and continuous way.

1. Applications to robotic arms and electrical prostheses:

Control of the movement of a cursor in a three dimensional scene is the most significant pattern in BCI based control studies. EEG changes, normally associated with left-hand, right-hand, or foot movement imagery can be used to control cursor movement.

Xu *et al,*(2011) used a robot-assisted upper-limb rehabilitation system, in translating patient’s intention to direct control of the rehabilitation robot. Features were extracted from the acquired signal through wavelet transform and a linear discriminant analysis(LDA) classifier was used to classify the pattern of left and right-upper-limb motor imagery. A personal computer triggers the upper-limb rehabilitation robot movements.

1. Applications to wheelchair control and autonomous vehicles

Traditional wheelchair control is done using joystick, but in certain cases of paralysis, brain control is a better option.

Tanaka *et al,*(2005) used a discrete approach for the navigation problem, in which the environment is discretized and composed by two regions (rectangles of 1m2 , one on the left and the other on the right of the start position), and the user decides where to move next by imagining left or right limb movements.

Rebsamen *et al,*(2010) used a P300-based (slow-type) BCI to select the destination in a list of predefined locations.

Iturrate *et al,*(2009) used a brain-actuated wheelchair based on P300 signals integrated in a real-time graphical scenario builder.

**2.1.2 Challenges of Brain Computer Interfacing**

According to Bonci *et al,*(2021), some of the general limitations of BCI technology are:

1. Inaccuracy in terms of classification of neural activity
2. Limited ability to read brain signals using non-invasive technology
3. In some cases, the requirement of surgery
4. The bulk nature of system leading to uncomfortable user experience
5. Ethical issues on reading inner thoughts and security of personal data from attackers or intruders.

Methods of recording brain activity are mostly causes of other forms of limitations.A major limitation of fMRI is the lack of image contrast. Setup and maintenance cost of PET is its major limitation. Motion artifacts, environmental noise, or eye movements can reduce the reliability of data acquired and can limit the ability of extracting relevant patterns. The features extracted from EEG are non-stationary due to changes among sessions that might not be monitored or controllable. For instance, the change in mental state or different levels of attention can affect the EEG signal characteristic and can increase its variability in different experimental sessions. In EEG signal acquisition, challenges concerning the identification of the optimal location for reference electrodes and the control of impedance when testing with high-density sponge electrode nets should be properly resolved. A relevant aspect related to the use of BCI concerns the trade-off between the difficulty interpreting brain signals and the quantity of training needed for efficient operation of the interface (Bonci *et al,*2021).

**2.1.3 Ethical and Legal Issues in Brain Computer Interfacing**

The possibilities of mind-reading and mind-conditioning in BCI poses serious ethical and legal issues for BCI technology. Brain-hacking and brain-phishing are possibilities that cannot be ignored, thus the need for policy-makers in the development of BCI technology.

As regards to mind-reading Vlek *et al,*(2012), discusses topics such as the representation of persons with communication impairments dealing with technological complexity and moral responsibility in multidisciplinary teams, and managing expectations, ranging from an individual user to the general public.

With reference to the mind-conditioning issue, the case of deep brain stimulation

(DBS) is discussed in Schermer, M.(2011). DBS is currently used to treat neurological disorders such as Parkinson’s disease, essential tremor, and dystonia and is explored as an experimental treatment for psychiatric disorders such as major depression and obsessive compulsive disorder. Fundamental ethical issues arise in DBS treatment and research, the most important of which are balancing risks and benefits and ensuring respect for the autonomous wish of the patient.

**2.2 POST STROKE UPPER-LIMB STROKE REHABILITATION**

A stroke or brain attack occurs due to blocked or burst brain vessel in the brain. As the brain cannot store oxygen, It relies on a network of blood vessels to provide it with blood that is rich in oxygen. A stroke results in a lack of blood supply, causing surrounding nerve cells to be cut off from their supply of oxygen. When tissue is cut off from its supply of oxygen for more than three to four minutes, it begins to die. Depending on the function of nerve cell damaged, body parts function are impaired or lost, due to lost communication between the damaged nerve cells and other cells of the body.

Stroke rehabilitation is a process by which those with disabling strokes undergo treatment by regaining and relearning the skills of everyday living. Stroke rehabilitation should begin almost immediately. It is believed that most of the recovery from strokes occur within the first 3-6 months but thereafter improvement is less likely. This can differ on a case-by-case basis.

Stroke can result in upper-limb motor impairment which results in functional limitations in using the affected upper-limb after stroke. Impairments may occur as impairment in body function or body structure.These impairments are not static, the nature of the impairment may change as motor recovery proceeds and there may be multiple impairment(Preeti Raghavan,2015).

Upper-limb impairments are best approached from the perspective of damaged or lost function. There are three main consequences of stroke on the upper limb which are: learned non-use, learned bad use and forgetting as determined by behavioral analysis of a task(Preeti Raghavan,2015).

Learned non-use occurs due to disuse of the affected upper-limb due to weakness/paralysis or sensory loss which may become habitual overtime and the limb may not be involved in functional activities, even though the individual can move it eventually becoming a learned behaviour(Preeti Raghavan,2015).

Learned bad use occurs in the absence of appropriate feedback and correction of abnormal motor behaviour when using compensatory strategies to complete movement tasks in cases of abnormal movement due to forced limb movement. Thus the patient is learning to use the limb in the wring way(Preeti Raghavan,2015).

Continually retaining a motor skill learned through training is expected in the absence of consistent training. However, rats with motor cortex injury show a decline in performance during intervals of no training and additional training is required to recover performance to previous levels before training. Breaks in rehabilitation similarly lead to forgetting of upper extremity motor skills in humans after stroke. Thus new skills, although reasonably stable in healthy individuals, are more transient after stroke(Krakauer JW, 2006).

**2.2.1 Stroke Neuro-Rehabilitation**

Until the 1950s, post-stroke patients were discouraged from being active after stroke. After the 1950s, therapeutic exercises were prescribed to patients from which good outcome was considered to be achieving a level of independence in which patients are able to transfer from the bed to the wheelchair without assistance.

In the earyly 1950s, Twitchell studied recovery pattern in stroke-patients. He found that if there is some recovery of hand function within four weeks, there is a 70% chance of making a full or good recovery. Twitchell reported that most recovery happens in the first three months and minor recovery occurs after six months.

There are majorly three classes of therapeutics for stroke neuro-rehabilitation which are:

1. Motor Re-learning: This is achieved through constrain-induced movement therapy or mental-imagery of movement tasks. In the former, affected patients are forced to use affected parts while constraining movement of normal working parts.
2. Brain Repair: This can be achieved through a technology called Functional Electrical Simulation where electrical stimulation mimics the action of healthy muscles to improve weak muscles. There is also robotic-rehabilitation where robot-assisted training enables stroke patients with moderate or severe upper limb impairment perform repetitive tasks in a highly consistent manner, tailored to their motor abilities and disabilities. These therapies have achieved the highest level of evidential support by the American Heart Association (Class I, Level of Evidence A) for the outpatient and chronic care settings and Class IIa Level of Evidence for the inpatient setting(Winstein CJ etal, 2016).

**2.2.2 Stroke Robotic-Rehabilitation**

Stroke robotic-rehabilitation emphasizes intense, highly repetitive and task-oriented movements so as to increase accuracy and functional use in subjects with stroke-induced paresis.

Stroke robotic-rehabilitation promotes cost-effective use of human resources and rehabilitation programs standardization. It also allows physiotherapist focus on functional rehabilitation during individual training and supervising patients simultaneously during robot-assisted therapy sessions, thus paying less attention to labor-intensive parts(Masiero, Poli,Rosati,et al).

To decrease the dependence on therapists, automated electro-mechanical gait machines have been developed. Gait machines comprise an electromechanical solution with two driven foot plates that simulate the phases of gait (i.e., the ‘Gait Trainer’,Schimdt H,et al) or a robot-driven exoskeleton orthotic system such as ‘Lokomat’ (Riener H,et al). ‘Lokomat’ is a computer-controlled robotic gait orthotic system that guides the patient in which gait training is automated, following a preprogrammed gait pattern. Gait training with the ‘Gait Trainer’ is also automated.

Wagner et al. performed an economic analysis of robot assisted therapy for long-term upper limb impairments after stroke compared with intensive traditional therapy and standard care. At 36 weeks post-randomization, the total costs were comparable between the three groups, and changes in quality of life were modest and did not differ significantly.

Stroke robotic-rehabilitation offers optional extra-features such as interaction and stimulation, extrinsic feedback.

**2.2.3 Robotic Devices-Machine for Upper Limb Rehabilitation**

(Massiero,Poli,Rosati et al).Existing upper limb robotic systems can be classified by:

1. The upper limb function on which they focus
   1. Unilateral
   2. Bilateral shoulder, elbow, wrist or hand movements
2. Mechanical characteristics:
   1. Exoskeleton
   2. Operational machines(End effector based machines)
3. Control strategy:
   1. Passive movement
   2. Active non-assisted
   3. Active assisted or Resistive mode
   4. Bi-manual exercise

**2.3 ELECTRONIC SPEED CONTROLLER(ESC)**

An electronic speed controller(ESC) is an electronic device designed to generate control signals which control the direction of angular-motion and angular-speed of brush-less direct-current(BLDC) motors.

**2.3.1 Brushed Motor Working**

A BLDC motor is a direct-current(DC) motor which makes use of three-phase electromagnetic coils(star-connected) as its stator and makes use of pairs of permanent magnets as its rotor.

Brushed motors on the other hand make use of permanent magnets on the outer body as the stator, electromagnets inside as the rotor and mechanical commutation through brushes. The structure of brushed DC motors(the placement of the brushes and commutator) and interaction between the excited electromagnet and the permanent magnets is such that there is no need for an electrical control-scheme to generate control signals for the electromagnet so as to start and maintain rotational-motion. The electromagnet(rotor) is placed within the magnetic field of the permanent-magnet(stator) such that current passed through the electromagnet is perpendicular to the permanent-magnet magnetic field while generating flux for the electromagnet(rotor) which interacts with the permanent-magnet field to generate force perpendicular to the current and the magnetic field in a direction given by flemmings left hand rule. The motion of the coil and the placement of brushes and commutator changes the direction of current through the electromagnet as required.

Unlike the brushed motors, which employ mechanical commutation through the use of brushes, BLDC motors do not make use of brushes or any other mechanical means for commutation, thus the need for electrical means of commutation.

**2.3.2 Advantages of Brushed Direct-Current Motor**

1. High starting torque: Brushed motors are preferred for applications that need to get up to speed very quickly as they have high starting torque compared to their brush-less counterpart.
2. Low cost: Brushed motors are of low cost compared to their brush-less counterpart, partly because they do not require special controllers to run.
3. Compatibility with industrial environments: Brushed motors are preferred in industries as they generally have high-starting torque.

**2.3.3 Disadvantages of Brushed Direct-Current Motor**

1. Increased Maintenance: Due to the effects of friction on a motor’s carbon brushes, they will naturally wear over time. As a result, brushed electric motors are more likely to require some sort of maintenance in the form of brush cleaning or replacement.
2. Lower speed:  Despite a high starting torque, brushed motors are not as capable of maintaining high-level speeds. This is because running a brushed motor at a consistent high speed can cause it to get warm.

**2.3.4 Brush-less Direct-Current Motor**

Electronic commutation make BLDCs popular.This replaces the conventional mechanics comprised of brushes rubbing on the commutator to energize the windings in the armature of a DC motor.Electronic commutation provides greater efficiency over conventional DC motors with improvements  of 20 to 30% for motors running at the same speed and load. Further, the BLDC motor is more durable. It retains its high performance while the efficiency and power of an equivalent conventional motor declines due to wear, causing poor brush contact, arcing between the brushes and the commutator dissipating energy, and dirt compromising electrical conductivity. Greater efficiency allows BLDC motors to be made smaller, lighter and quieter for a given power output, further increasing their popularity in sectors such as automotive; white goods; and heating, ventilation and air conditioning (HVAC). Other advantages of BLDC motors include superior speed versus torque characteristics (with the exception of torque at start-up), a more dynamic response, noiseless operation, and higher speed ranges. The downside of BLDC motors is their complexity and the associated increase in cost. Electronic commutation demands supervisory circuits to ensure precise timing of coil energization for accurate speed and torque control, as well as ensuring the motor runs at peak efficiency.

All electric motors, whether mechanically or electronically commutated, adhere to the same basic method of converting electrical energy into mechanical energy. Current through a winding generates a magnetic field, which in the presence of a second magnetic field (typically initiated by permanent magnets) generates a force on that winding that reaches a maximum when its conductors are at 90° to the second field. Increasing the number of coils raises the motor output and smooths power delivery.

A BLDC motor overcomes the requirement for a mechanical commutator by reversing the motor set-up; the winding's become the stator and the permanent magnets become part of the rotor.Because the winding's are stationary, permanent connections can be established to energize them. In order for the stationary winding's to move the permanent magnet, the winding's need to be energized (or commutated) in a controlled sequence to produce a rotating magnetic field. Because the rotating magnetic field generated by the stator causes the rotor to revolve at the same frequency, a BLDC motor is known as a “synchronous” type. BLDC motors can come in one-, two-, or three-phase.

**2.3.5 Brush-less Direct-current Motor Control**

The most common method for BLDC motor control is the use of three half-bridge MOSFET configuration, each one for switching each phase of the BLDC motor. The high-side of the half-bridges are controlled using pulse-width-modulation(PWM) which limits start-up current and offers precise control over speed and torque and also trade-off between high-frequency switching losses and low-frequency ripple current.Typically, designers use a PWM frequency of at least an order of magnitude higher than the maximum motor rotation speed. There might be need for positional feedback to the controller so as to generate the next control signal for the half-bridges depending on the adopted control scheme.

There are three control schemes for electronic commutation which are trapezoidal, sinusoidal and field-oriented control.

1. Trapezoidal control scheme: At each step, two winding's are energized (one “high” and one “low”) while the other winding floats. The downside of the trapezoidal method is that this stepped commutation causes the torque to ripple, especially at low speeds.
2. Sinusoidal control scheme: This is more complex, but it reduces torque ripple. All three coils remain energized with the driving current in each of them varying sinusoidally at 120° from each other. The result is a much smoother power delivery compared with the trapezoidal technique.
3. Field-oriented control scheme: This relies on measuring and adjusting te stator current so that the angle between the rotor and stator flux is always 90°. This technique is more efficient at high speeds than the sinusoidal method and gives better performance during dynamic load changes compared to all other techniques. There is virtually no torque ripple, and smoother, accurate motor control can be achieved at both low and high speeds.

**2.3.5.1 Positional feedback**

Two technologies offer a solution for positional feedback. The first and most common uses three Hall-effect sensors embedded in the stator and arranged at equal intervals, typically 60° or 120°. A second, sensor-less control technology comes into its own for BLDC motors that require minimal electrical connections.

1. Sensored: In a sensor-equipped BLDC motor, each Hall-effect sensor is combined with a switch which generates a logic “high” (for one magnetic pole) or “low” (for the opposite pole) signal. The commutation sequence is determined by combining the logic signals from the Hall-effect sensors and associated switches. At any time, at least one of the sensors is triggered by one of the rotor’s magnetic poles and generates a voltage pulse.
2. Sensor-less: A sensor-less BLDC motor makes use of the electromotive force (EMF) that gives rise to a current in the winding's of any DC motor with a magnetic field that opposes the original change in magnetic flux as described by Lenz’s Law. The EMF tends to resist the rotation of the motor and is therefore referred to as “back” EMF.

By monitoring the back EMF, a suitably programmed micro-controller can determine the relative positions of the stator and rotor without the need for Hall-effect sensors. This simplifies motor construction, reducing its cost as well as eliminating the additional wiring and connections to the motor that would otherwise be needed to support the sensors, thus improving reliability.

However, because a stationary motor generates no back EMF, the controller is unable to determine the motor position at start-up. The solution is to start the motor in an open loop configuration until sufficient EMF is generated for the controller to determine rotor and stator position and then take over supervision. A more sophisticated control regime is used if the motor is used in an application where reverse rotation is forbidden.

**2.3.6 Advantages of Brush-less Direct-Current Motor**

1. Long lifespan: As brush-less DC motors do not have brushes, they require less maintenance as mechanical motion and friction does not wear out any commutation part
2. Efficiency: The absence of brushes in brush-less DC motors means that no speed is lost due to friction. This makes brush-less DC motors typically 5-90% efficient compared with their brushed counterparts at a typical efficiency 75-80%
3. Quiet operation: Due to the lack of brushes, brush-less motors run extremely quietyl and have particularly smooth operation. This is useful for applications that require such properties such as the development of medical robots, patient hoists, etc.

**2.3.7 Disadvantages of Brush-less Direct-Current Motor**

1. Requires a controller: Brush-less DC motors need to be wired to an electronic sped controller(ESC), to enable current to flow through the electromagnets.
2. Cost: Due to the requirement of an electronic speed controller, brush-less DC motors can be more expensive.

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