CHAPTER 1
INTRODUCTION

1.1 Background of Study

Back in 2001, world's first self-balancing personal transporter has been introduced to the public. This new concept of personal transportation gives more advance and mobility to all users all around the world. It represent the next generation in personal mobility, offering several advancements that make the ride even more intuitive and productive than ever before.

The self balancing system of the personal transporter is a new technology discovered by Segway Incorporated. It's start from Kamen's model of example – human body; as human stands up and leans forward until out of balanced but will not fall on face. It's because human brains know by the fluid in the inner ear shifts, so it will ask legs to move forward to prevent from falling. It's same if the body tends to fall backward then brains will be putting legs to take a step backward to stabilize the body itself again.

In Segway – PT, the balancing system is controlled by intelligent network of sensors, mechanical assemblies, propulsion and also control system. Five gyroscopic sensors are being attached of the Segway – PT platform. Three of the gyroscopic sensors are use to detect leaning forward or backward (*pitch*), leaning to the left of right (*roll*) and steering to left of right (*yaw*). The other two gyroscopic sensors used as redundancy to make all the system more reliable.

Thus, by applying from human body model; microprocessor in the Segway – PT will act like a brain in the system. When gyroscopes detect the direction of the movement it will then send signal to microprocessor to translate faster than a blink of an eye; motor will move the Segway forward.

There are lots of advantages by using Segway – PT compare to other type of transportation. From environmentally aspect, Segway – PT do not produce any CO_2 like any other cars do. CO_2 will just keep the "Green House Effect" at high risk and global warming occurs more rapidly from years to years.

By walking or cycling, lots of calories will be used and the travel distances are less compare to capability of Segway – PT. It does not use lots of human calories and can also travel more. As in a research paper said that for a cyclist to travel 100km with maintaining the speed at 30km/h, it requires 20-30kcal of human energy per kilometer [1].

Daily Activities Calories Per Minute

	Weight (pounds)					
Activity	**110**	**130**	**150**	**170**	**190**	**210**
Cooking	1.7	2.0	2.3	2.6	2.9	3.2
Eating	1.3	1.4	1.5	1.6	1.7	1.8
Sex (intercourse)	4.0	4.5	5.0	5.5	6.0	6.5
Showering/Dressing	2.6	3.0	3.4	3.8	4.2	4.6
Sitting Talking	1.3	1.5	1.7	1.9	2.2	2.4
Sleeping	0.9	1.0	1.1	1.2	1.3	1.4
Swimming (crawl)						
20 yds per min.	3.9	4.5	5.1	5.7	6.3	6.9
30 yds per min.	5.5	6.3	7.1	7.9	9.7	10.5
35 yds per min.	7.1	8.0	8.9	9.8	10.7	11.6
40 yds per min.	7.8	8.9	10.0	11.1	12.2	13.3
45 yds per min.	9.0	10.3	11.6	12.9	14.2	15.3
55 yds per min.	11.0	12.5	14.0	15.5	17.0	18.5
Bicycling						
5.5 mph	3.2	3.6	4.0	4.4	4.8	5.2
10 mph	5.4	6.2	7.0	7.8	8.6	9.4
13 mph	8.6	9.8	11.0	12.2	13.4	14.6
Running						
5.5 mph	8.6	9.8	11.0	12.2	13.4	14.6
6.0 mph	8.8	9.9	11.0	12.1	13.2	14.3
6.5 mph	8.9	10.2	11.5	12.8	14.1	15.4
7.0 mph	9.2	10.4	11.6	12.8	14.0	15.2
7.5 mph	9.8	11.2	13.6	16.0	18.4	19.8
8.0 mph	10.4	11.9	13.4	14.9	16.4	17.9
8.5 mph	11.2	12.8	14.4	16.0	17.6	19.2
9.0 mph	12.0	13.8	15.6	17.4	19.2	21.0
9.5 mph	12.8	14.7	16.6	18.5	20.4	22.3
10.0 mph	13.6	15.5	17.4	19.3	21.2	23.1
10.5 mph	14.3	16.3	18.3	20.3	22.4	24.3
11.0 mph	15.2	17.3	19.4	21.5	23.7	25.9
11.5 mph	15.9	18.2	20.5	22.8	25.1	27.4
12.0 mph	18.2	20.7	23.2	25.7	28.2	30.7
12.5 mph	20.3	23.1	25.9	28.7	31.5	34.3

Table 1.1: Daily Activities Calories per Minute [2]

1.2 Problem Statement

In such personal transport, balancing is the main issue. Balancing a person who's standing on it is necessary to avoid any unexpected incident. Thus a self balanced personal transporter is needed as a safety precaution. Nevertheless without a self balancing system in the transporter, learning curve to ride this transportation will be much longer. In other words people will take more time to learn to ride this personal transporter.

As briefly on previously part about the technology of the Segway – PT, it is obviously that Segway – PT use high-cost electronic component and this gives impact to the cost of each transporter. As mentioned in page 1, for industrial purposes a Segway – PT will cost around $8000 which is about RM29000 and for consumer purposes will cost around $3000 which is RM11000 in our currency.

No solution for alternative for this personal transporter to be cost effectively until now. This gives bad impact to the marketing of the product itself. Comparatively with a national car, PERODUA Kancil 850EX for example will sot around RM28000. For some people they will have to think twice to buy a Segway – PT product, in fact they will prefer to buy a car instead of personal transporter.

Economically other transports might not be a good idea for daily usage, as oil price is fluctuating ups and down. Compare to electricity cost per year by using Segway is cheaper rather than using a car with a high gasoline cost per year [3]. Thus personal transporter is an alternative that is suitable in a condition of economic nowadays.

Many people are getting more vehicles for their daily usage. The increasing of vehicle used on the road has been seriously by lots of environmentalist as it is one of the causes that make nature pollute. Releasing CO_2 widely will cause a layer of it in the atmosphere and prevent heat to be released freely. Thus creating global warming phenomena or known as "Green House Effect"

1.3 Objective and Scope of Study

The objective of this project is to propose a self-balancing system for a personal transporter and it will cost less than Segway – Personal Transporter. This will cater problem of rider to fall from the personal transporter for the cause of balancing.

Even though the vision of this project is to produce whole new alternative for Segway – PT, however author will only focusing on balancing system. The deliverable output of this project will be a scaled model of single platform that able to balance itself when a load is put on it.

1.4 Significance of the Project

A good balancing system will provide useful info for the PT designers. The user will be confident quickly in using the PT and the overall cost of the PT can be reduced by much. As the balancing system is a core component and relatively more expensive that other component of PT [4].

Directly, this technology will be available in our society. Public are having chances to enjoy this technology widely. Not just in that, society surrounded would also able to learn and increase their knowledge more about this technology in their life.

Life in congested traffic area would also be better, as personal transporter might be a better alternative to avoid traffic congestion and at the same time economically better for not using fuel as power source. Indirectly, less pollution will be made by human. Not just air pollution but sound pollution also will be better from time to time. What we want more from a green world and technology in there?

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 Existing System Available

In a few articles, it is shows that Segway – Personal Transporter is in under inverted pendulum concept. This concept explained as in example of a unicycle, the rider of a unicycle need to maintain a combination of balance and rear/forward motion to keep upright and it is inherently unstable. Considered for Segway – Personal Transporter, the wheels is in parallel instead of a bicycle with two wheels inline of each other which will constrains the movement for the pendulum within a single dimensional axis. For Segway – Personal Transporter, it balance itself in an upright position by using five silicon gyroscopes together with sophisticated electronic closed loop feedback control algorithm [5].

Particularly, gyroscopes use in Segway – Personal Transporter is fluidic tilt sensor type as it has a small time-varying bias. With a low pass filter and integral term is added to rack out any accumulated error and keep the system stable as well. The gyroscopes detect both positive pitches (leaning forward and backward). The rate is detected by gyros and the motor will apply its torque for the wheels to be back to its null position when rider leans forward [6].

In term of performance-wise, balancing machine present unique benefits and challenges when compared to statically stables machines. For example, a balancing machine can turn with zero radiuses and can carry a large payload much higher than a comparable weight statically stable base. But dynamically stabilized machine can fall over and "the taller they are, the hard they fall". There are differences present both challenges and opportunities in mobile robot research [5].

Trevor Blackwell made an improvement by making his personal transporter lighter, smoother and faster. He changed previous gyroscope to the CRS03-02 from Silicon Sensing Company and changed ADXL105 accelerometer to ADXL102 accelerometer for it to have a higher saturation of thresholds [8].

Invented by another man, Earl W. Bollinger; he is also manage to do a simpler and low cost a self balancing robot. As well as Segway use a 5-gyroscopic sensors to detect and give signal to the controller of balancing system it will also costly more. Thus E. W. Bollinger has created a combo sensor that are cheaper than what Segway has been used. It is combination of gyro-accelerometer sensor where each of them known as ADXRS150 and ADXRS300 which are low cost and low power with high performance [9].

A robot known as nBot also has been invented by David P. Anderson. Although the robot is quite small but it was featured as NASA's Cool Robot of the Week for 19 May 2003 and honored by the NASA page as one the top 10 engineering and technical web sites for 2003 [10]. In this article, it is stated that there are four terms are sufficient to define the motion and position of this "inverted pendulum" and thereby balance the robot. There are:

a) The tilt angle.
b) Its first derivative; the angle velocity.
c) The platform position.
d) Its first derivative; the platform velocity.

These four measurements are summed and fed back to the platform as a motor voltage, which is proportional to torque, to balance and drive the robot [10].

2.1.1 Theory of Inverted Pendulum

An inverted pendulum is a pendulum which has its mass above its pivot point. It is often implemented with the pivot point mounted on a cart that can move horizontally and may be called a cart and pole. Whereas a normal pendulum is stable when hanging downwards, an inverted pendulum is inherently unstable, and must be actively balanced in order to remain upright, either by applying a torque at the pivot point or by moving the pivot point horizontally as part of a feedback system.

There are 2 types of inverted pendulum; which are fixed suspension point and also moving suspension point. In this personal transporter, moving suspension point is more related to the project. Thus author revise about this theory as a part of balancing knowledge [11].

Consider a pendulum, the suspension point of which is situated at the centre *O* of a wheel. The wheel, which is symmetrical about its axis *O*, can roll without sliding over a flat horizontal surface in a straight line. Denote the mass of the wheel by *M*, its radius by *R* and the radius of inertia about the centre *O* by ρ. Denote the angle of counterclockwise rotation of some fixed radius (marked on the wheel), which, at the start of the motion, is directed along the horizontal axis *X*, by φ and denote by *x* the displacement of the centre of mass *O* along a horizontal straight line such that $\dot{x} = -\dot{\varphi}R$. As above, suppose β is the angle of deflection of the pendulum from the vertical, *m* is its mass, *b* is the distance from the suspension point *O* to its centre of mass and *r* is the radius of inertia of the pendulum about the suspension point *O*. Assume that an electric motor is mounted on the axis of the wheel with its stator rigidly fastened to the wheel and its rotor rigidly fastened to the pendulum. Suppose torque *L*, developed by this motor, tend to rotate the pendulum counterclockwise and simultaneously tends to rotate the wheel clockwise. Hence, *L* is an internal torque [11].

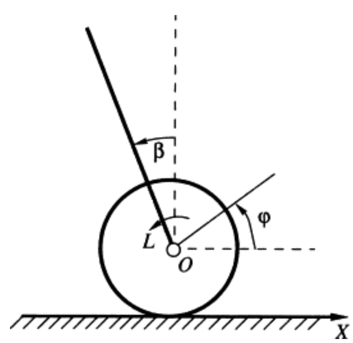

Figure 2.1: Inverted Pendulum Illustration [11].

This shown that when a pendulum (mass) on the wheel is not stable, the wheel below will directly move to the right or to the left to make the pendulum (mass) above become stable again.

2.2 Theory of gyroscopes

A gyroscope is a device for measuring or maintaining orientation, based on the principles of angular momentum. The device is a spinning wheel or disk whose axle is free to take any orientation. This orientation changes much less in response to a given external torque than it would without the large angular momentum associated with the gyroscope's high rate of spin.

Within mechanical systems or devices, a conventional gyroscope is a mechanism comprising a rotor journal to spin about one axis, the journals of the rotor being mounted in an inner gimbal or ring, the inner gimbal being journal for oscillation in an outer gimbal which in turn is journal for oscillation relative to a support. The outer gimbal or ring is mounted so as to pivot about an axis in its own plane determined by the support. The outer gimbal possesses one degree of rotational freedom and its axis possesses none. The inner gimbal is mounted in the outer gimbal so as to pivot about an axis in its own plane that is always perpendicular to the pivotal axis of the outer gimbal.

The axle of the spinning wheel defines the spin axis. The inner gimbal possesses two degrees of rotational freedom and its axis possesses one. The rotor is journal to spin about an axis which is always perpendicular to the axis of the inner gimbal. So, the rotor possesses three degrees of rotational freedom and its axis possesses two. The wheel responds to a force applied about the input axis by a reaction force about the output axis.

Once the gyroscope is spin, the effect of that entire axle wants to keep pointing in the same direction. The basis of the gyro-compass is when gyroscope is mounted in a set of gimbals and it continues pointing in the same direction. If two gyroscopes mount with their axles at right angles to one another on a platform, and place the platform inside a set of gimbals, the platform will remain completely rigid as the gimbals rotate in any way they please. This is called as Inertial Navigation System (INS). In other application, gyroscopes also being used in space shuttle, airplane compass and autopilot, the Russian Mir space station to keep its orientation to the sun and also the Hubble Space Telescopes [12].

2.3 Types of Sensor & Controller

As stated in the section 2.1 in E. W. Bollinger research, types of sensor he did use in his self-balancing robot is by having gyro-accelerometer combo circuit which is cost less, consume less power and also in high performance as well. Below is the diagram of the combo circuit using by E. W. Bollinger:

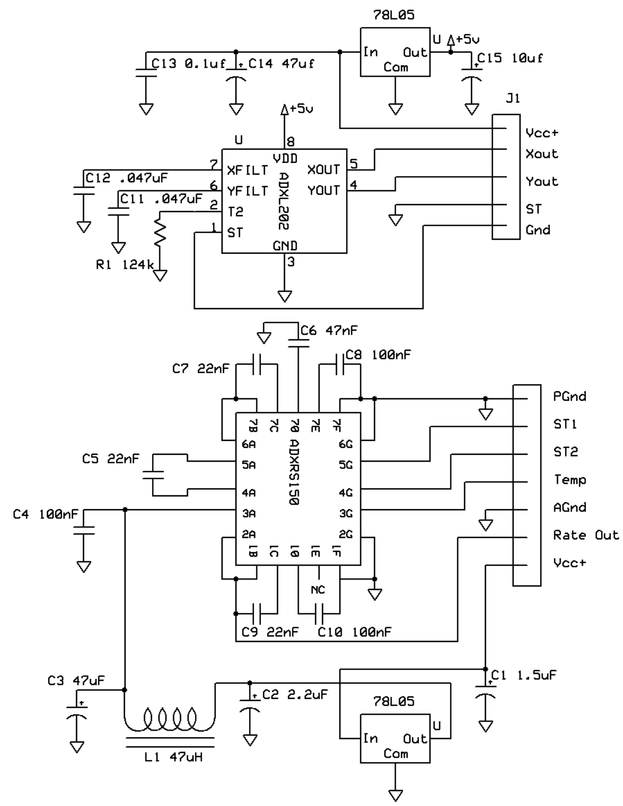

Figure 2.2: Schematic Diagram of Gyro-Accelerometer Sensor [9].

In a comparative article in a website, Gary Felsing [13] states that gyroscopes sensor is the best sensor approach to be used in any application. It is because gyroscopes measures rotational motion, not influence by gravity, both frequency and magnitude information accurate down to DC(zero frequency), only a single integration is needed to obtain angular displacement, high signal to noise ratio, high dynamic range, solid state gyros do not influence motion of subject being measured and no intimate electrical contact with subject.

Below is the summary of comparison between gyroscopes and accelerometer [13]:

GYROSCOPE	ACCELEROMETER
Measure rotational motion	Measure linear motion and gravity
Not influence by gravity	Signal magnitude corrupted by gravity
Both frequency & magnitude information accurate down to DC	Frequency data good but bandwidth often not down to DC
Single integration needed to obtain angular displacement	Difficult second integration required to obtain displacement

Table 2.1: Comparison between gyroscopes and accelerometer

PI observer-based fault is a diagnosis scheme which contains the strategies of fault-detection and fault-evaluation of actuator malfunction. It has been verified that the proposed control system has benefits such detecting possible failure of the experimental personal transporter [7].

While any feedback controller can tolerate plant variation (that is the point of feedback after all), a basic LQR controller for a balancing machine does not produce the same balancing dynamic regardless of payload. Thus the controller must be matched to the mass properties of the RMP (inertia, mass, center of gravity) [5].

2.3.1 Theory of LQR controller

Linear Quadratic Regulator (LQR) has a pole placement for controller design relies on specification of the desired closed loop poles of the system. This is usually difficult to specify, especially for systems with large number of states. Further, with pole placement design there is no consideration given to the “amount” of actuation (called actuation effort) that gets used during closed loop operation.

Good regulation of the system can usually be achieved by using high amount of actuation (i.e. higher K_p, and thus greater actuation effort, in a P-controller gives faster rise time). Ideally it is to achieve good system performance while at the same time minimizing the amount of actuation used in achieving the desired performance [14].

One way of expressing this mathematically is through an objective function of the form:

$$J = \underbrace{\int_0^\infty x^T Q x dt}_{regulation} + \underbrace{\int_0^\infty u^T R u dt}_{Actuation}$$

The LQR design problem is to design a state-feedback controller K such that the objective ***J*** is minimized. For simplicity we assume that matrices ***Q*** and ***R*** are diagonal. Thus, the objective ***J*** reduces to:

$$J = \underbrace{q_1 x_1^2 + \ldots + q_n x_n^2}_{regulation} + \underbrace{r_1 u_1^2 + \ldots + r_m u_m^2}_{actuation}$$

The scalars $q_1,\ldots, q_n, r_1,\ldots,r_m$ can be looked upon as relative weights between different performance terms in the objective ***J***. The key design problem in LQR is to translate performance specifications in terms of the rise time, overshoot, bandwidth, etcetera into relative weights of the above form. There is no straightforward way of doing this and it is usually done through an iterative process either in simulations or on experimental setup. Once the matrices ***Q*** and ***R*** are completely specified, the controller gain ***K*** is found by solving the Riccati equation[14].

CHAPTER 3
METHODOLOGY

3.1 Process Flowchart

This chapter describe the methodology employed in coming up with the design of the balancing system. The steps taken are starting from FYP I until FYP II completion date.

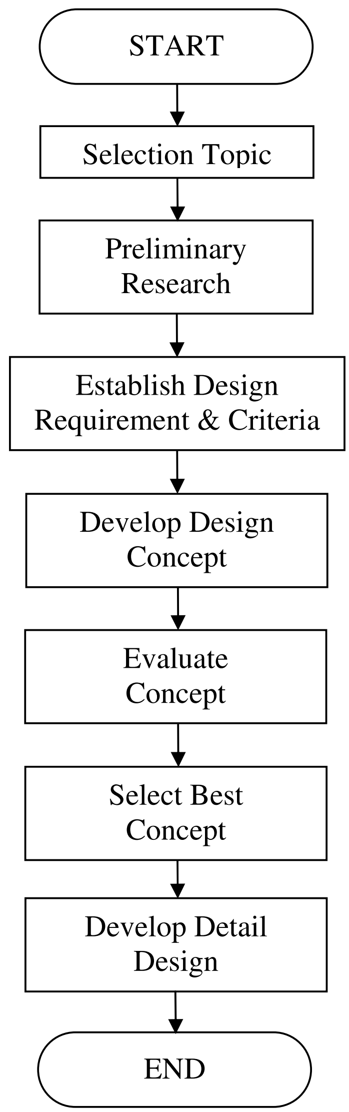

Figure 3.1: Process Flowchart

3.1.1 Establish Design Requirement

In this method, author will set design specification based on finding of literature review. Design requirement is basically a specification that might be change from time to time based on result or finding on other literature review.

3.1.2 Design Criteria

From design specification, author will finalize the design criteria that need to be used or as to be guidelines in the project to be achieved.

3.1.3 Analyze Design Criteria

The design criteria will be evaluate and to be analyze in each aspect for it to be considered in the design concept. This process maybe has repetition as design will always change from time to time depend on the findings.

3.1.4 Develop Design Concept

From a set of criteria that has been listed and been analyzed, author will be used the finalized criteria to be concluded and developed in the design concept.

3.1.5 Analyze Design Concept

The design concept will then to be analyzed to make sure all the specifications are met up to the standard and feasible in few factors.

3.1.6 Develop Detail Design

In this section, complete detail design will be concluded together with the help of few drawings and this is the completed design of the project.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Establish Design Requirement/Criteria

Referring to the Trevor Blackwell and David P. Anderson model, both of them use 2 DC motor to operate the balancing system on their personal transporter and also balancing robotics. Both motors are powered by NiMH cell batteries but just different amount of them are used in both machine.

In sensors point of view, both of the T. Blackwell and D. P. Anderson model are using the gyro-accelerometer combo circuit. Not only are them using the type of sensor circuit, but also for Earl. W. Bollinger that used the combo circuit for each of their machines. The gyro-accelerometer not only cost less, it also low power but with a high performance.

Based on preliminary research, few criteria can be list out but however these criteria are design specification (it may change from time to time and will be added throughout the project run).

The design specification:

1. Dimension of Platform: 30cm x 45cm
2. Maximum Tilt: ± 15 Degree
3. Maximum Payload: 100kg
4. Response Time: Less than 0.5 second
5. 2 DC motors
6. Gyro-accelerometer combo sensors circuit

4.2 Analyze Design Criteria

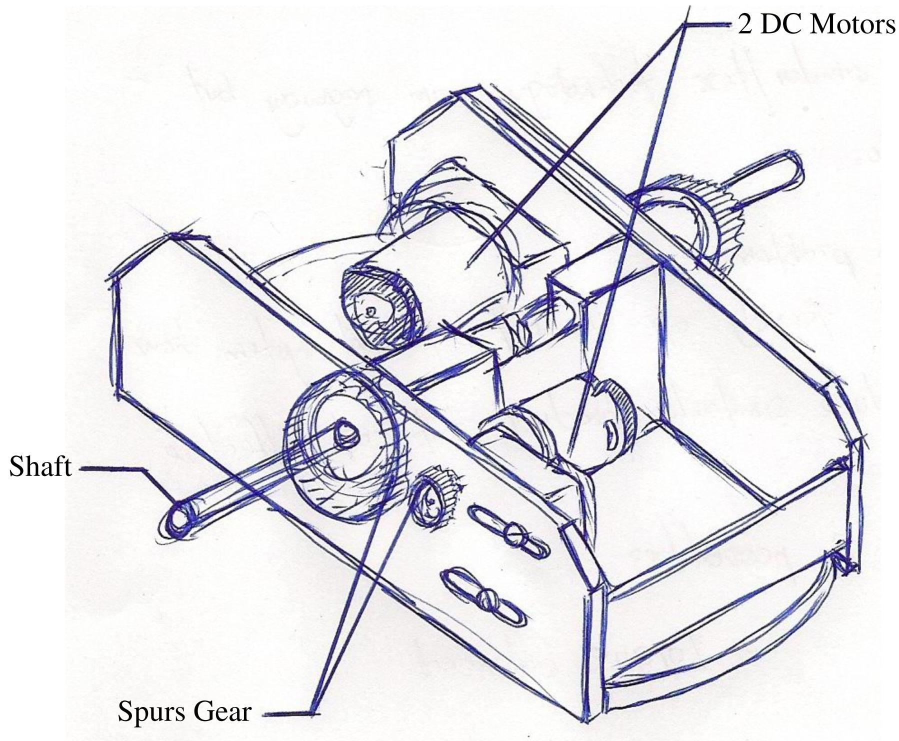

Figure 4.1: Design of the mechanical part of the balancing system.

Figure above show the orientation of the motor component, shaft, gears and the chassis. This is suggested by the author; however this model is based on scaled model not to an actual model as stated in the scope of study in this project. For gyro-accelerometer combo circuit, this is not being suggest for any alternative design because this circuits usually are available in the market and purchasing process will be needed.

However, few considerations of types of this circuit combo have been listed as below:

a) ADXRS150 and ADXL202E
b) Ceramic Rate Gyro and 2-axis accelerometer
c) Piezo-electric gyroscope and ADXL202 Accelerometer

4.3 Develop & Analyze Design Concept

4.3.1 Engineering Calculation

In this section, author will analyze on the maximum torque and also determine the suitable motor for this application.

Determine the maximum torque.

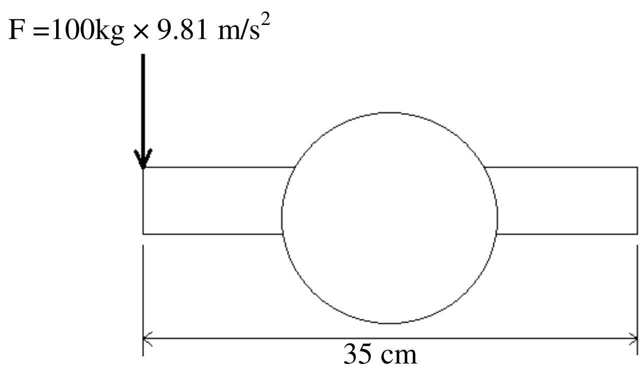

Figure 4.2: Schematic from side view of the platform and the wheel.

$$Torque,\ T = Force \times Distance = F \times r\cos(\theta)$$

Thus for this system, 1st case when $\theta = 0^o$:

$$T_{max} = Force \times Maximum\ Distance\ from\ center$$

$$T_{max} = 100\ kg \times 9.81 m/s^2 \times 0.175m = \underline{172\ N\cdot m}$$

For 2nd case when $\theta = \theta_{max} = 15^o$:

$$T_{max} = Force \times Maximum\ Distance\ from\ center$$

$$T_{max} = 100\ kg \times 9.81 m/s^2 \times 0.175m \times \cos 15^o = \underline{166\ N\cdot m}$$

Thus, from this two case the maximum torque will be $T_{max} = 172\ N\cdot m$. But however for safety factor of 2 the T_{max} will be taken as $344\ N\cdot m$.

From the specification at page 14, response time is less than 0.5 second and maximum tilt is 15 degree.

The rotational velocity of the platform:

$$\frac{\left(\frac{30^\circ}{360^\circ}\right)}{s} \times \frac{60s}{1min} = 5\,rpm$$

For this application, rotational velocity of the motor will be at 1500 rpm. Thus the gear ratio can be calculated like below:

$$\frac{1500\,rpm}{5\,rpm} = \frac{300}{1}$$

Thus the gear ratio is 300:1. For torque, it is indirectly proportional to the gear ratio. From the calculation of the maximum torque produce at page 16, $T_{max} = 344\ N.m$. This value will be used to calculate the torque needed for selecting proper DC brushless servo motor.

$$\frac{344\,N.m}{300} = 1.15\,N.m$$

In conclusion, the motors must be able to meet this specification:

Rotational Speed: *1500 rpm*

Max Torque: *1.15 N.m*

4.3.2 Motors Selection

Basically they are 3 parameters that need to be considered; Max Torque, RPM, and Weight of the motors. But the most important for selecting the motor are the maximum torque and the RPM.

Author selects servo motors mainly because servo motors are typically is equipped with either encoder or resolver feedback. Thus it is suitable for closed loop control systems.

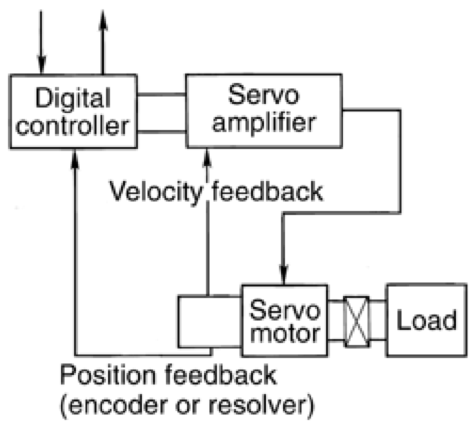

Figure 4.5: Typical DC servo motor system. [19]

Thus by having the velocity feedback at servo amplifier, the motors will compare to its programmed motion profile and readjust to be as close as possible to the programmed profile. Thus this increased the efficient of the motor compared to the motor without servo amplifier.

From DC motors catalogue, author found few high torque brushless servo dc motors which are suitable for this application. Following is the options for these motors.

First Option:

Model No.		QB01701		
Motor Constants				
Stall Torque (continuous)	oz-in	21.6		
	Nm	0.15		
Max Rated Torque	oz-in	169		
	Nm	1.19		
No Load Speed	RPM	1722	2286	4665
	rad/s	180	240	488
Motor Weight	oz	78.1		
	kg	2.24		

Table 4.1: Specifications on NEMA 17 [16]

Second Option:

Model No.		QB03401		
Motor Constants				
Stall Torque (continuous)	oz-in	33.5		
	Nm	0.23		
Max Rated Torque	oz-in	264		
	Nm	1.87		
No Load Speed	RPM	1413	1913	3802
	rad/s	148	200	408
Motor Weight	oz	103.3		
	kg	2.92		

Table 4.2: Specification on NEMA 34 [17]

Thus by comparing those 2 brushless servo dc motors:

	QB01701			**QB03401**		
	A	**B**	**C**	**A**	**B**	**C**
Maximum Torque (N.m)	1.15	1.19	1.19	1.55	1.87	1.87
Rotational Speed (RPM)	1722	2286	4665	1413	1913	3802
Weight of Motor (Kg)	2.24	2.24	2.24	2.92	2.92	2.92

Table 4.3: Comparison of NEMA 17 & NEMA 34

As calculated in page 16 & 17, calculated maximum torque is 1.15 N.m and the rotational speed is 1500rpm. Therefore from the motors catalogue, the most suitable motor would be QB01701 with rated maximum torque at 1.15 N.m and rotational speed at 1722 slightly a bit higher from requirement at 1500rpm.

4.3.3 Block diagram of the whole system

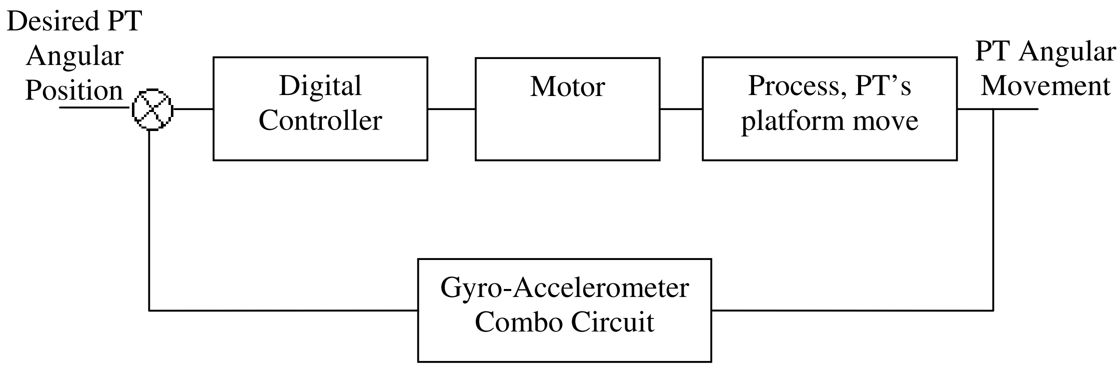

Figure 4.6: Balancing System Block Diagram

This is the design concept of the balancing system of the personal transporter. The entire component stated above is the main components that need to be included in the balancing system.

For power supply system, resistor voltage regulator need to be used in this system as the power supply from the battery need to be stepped down as to avoid damages on the combo circuit. Voltage regulator is used instead of transformers as transformers are suitable for alternating current to handling much bigger amount of power.

For voltage regulator, there are ratings for certain power input and output needed for it to function. Thus author suggest to using a model of manufacturer MAXIM Integrated Products from United States. Below are the details of the model:

- General Description:
  The MAX5082 is 250 kHz PWM step-down DC-DC converters with an on-chip, 0.3Ω high-side switch. The input voltage range is 4.5V to 40V for the MAX5082. The output is adjustable from 1.23V to 32V and can deliver up to 1.5A of load current.
- Features of the voltage regulator:
  - 4.5 V to 40 V (MAX5082) for range of voltage input
  - A Output Current
  - V_{OUT} Range from 1.23V to 32V

- ❖ Internal high-side switch
- ❖ Fixed 250 kHz internal oscillator
- ❖ Automatic Switchover to Pulse-Skip Mode at Light Loads
- ❖ External Frequency Synchronization
- ❖ Thermal Shutdown and Short-Circuit Protection
- ❖ Operates Over the -40°C to +125°C Temperature Range
- ❖ Space-Saving (5mm x 5mm) High-Power 16-Pin TQFN Package

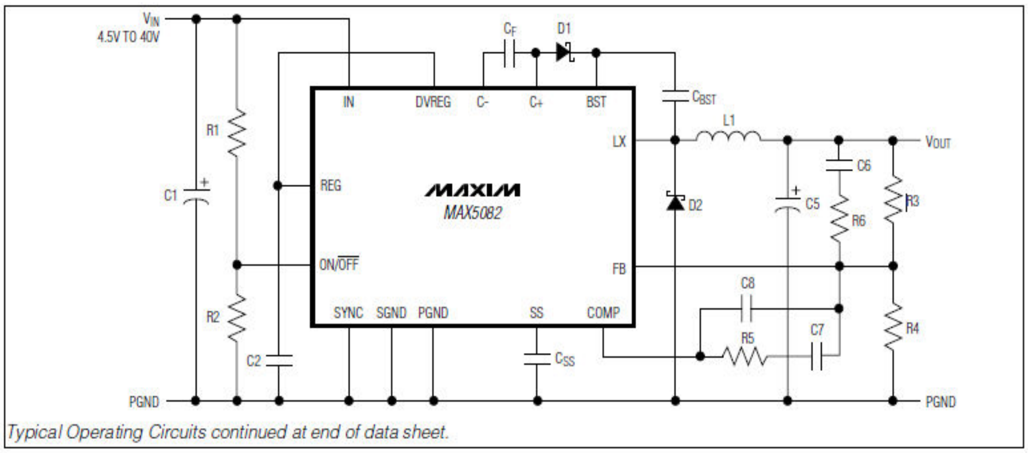

Figure 4.7: Typical Operating Circuits of Voltage Regulator.

For power supply source, author chooses NiMH battery as it's readily available in the market and also its characteristics are suitable for this type of application. NiMH cells have a characteristic of low internal resistance and this is advantageous for high current drain applications. NiMH can handle high current levels and maintain its full capacity. In addition, NiMH also has the ability to recharge hundreds of times that in long term effect it will save money and resources as well.

For the combo circuit, circuit of the gyroscope (ADXRS150) and circuit of accelerometer (ADXL202E) will be used. This is because gyroscope is a reliable sensor to detect any rotation angle in the platform. But it has weaknesses, other than major weakness of high costing; it has also problem of develops a slow creeping tilt error that continues to increase [9].

This mean that if the platform is tilt forward a few degrees and stay at that angle, the gyroscopes sensor will report that the platform is standing straight up after a second. So eventually the errors add up and the platform will falls over. By using an accelerometer it will helps to solve this problem. For this reason author used circuit of accelerometer model ADXL202E, this is because accelerometer has outputs of steady duty cycle when the platform is standing straight up and if the platform tilts one way or the other way around it will changes slowly until the platform is steady again.

- Features of the accelerometer circuit:
  - 2-Axis Acceleration Sensor on a Single IC Chip
  - mm _ 5 mm _ 2 mm Ultra small Chip Scale Package
  - mg Resolution at 60 Hz
  - Low-Power < 0.6 mA
  - Direct Interface to Low-Cost Microcontrollers via Duty Cycle Output
  - BW Adjustment with a Single Capacitor
  - V to 5.25 V Single Supply Operation
  - 1000 g Shock Survival

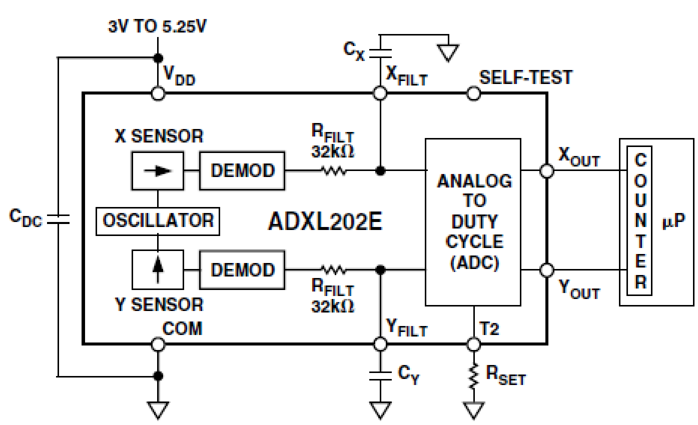

Figure 4.8: Block Diagram of the Accelerometer Circuit

4.3.4 Economics Comparison

As stated in the objective of this project; to proposed a design that is cost efficiently. Thus in this section, author will brief about all the cost needed to make this system.

Components	Price (RM)
Motors (2 units)	784
Gyro-Accelerometer Circuit Board	236
Voltage Regulator	80
NiMH Battery	473
Others accessories	300
TOTAL	**1823**

Table 4.4: Basic Cost of Proposed Design

However, price of component from Segway – Personal Transporter could not be obtained for author to compare side by side. As balancing system is the core part of a personal transporter, the biggest percentage of cost will go in this part of system. It is estimated for the total project would be around RM 2000 – RM4000 and if compare the cost of the total project with Segway – PT, the proposed design is much cheaper than what Segway – PT offer as the cheapest Segway – PT model would cost around RM13000.

4.3.5 Technical Drawings of Complete Design

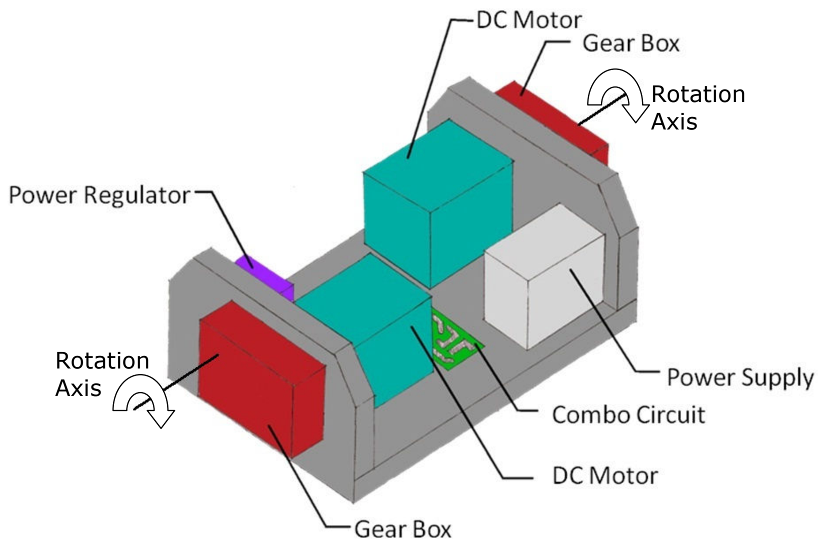

Figure 4.9: Detail Design of the Balancing System

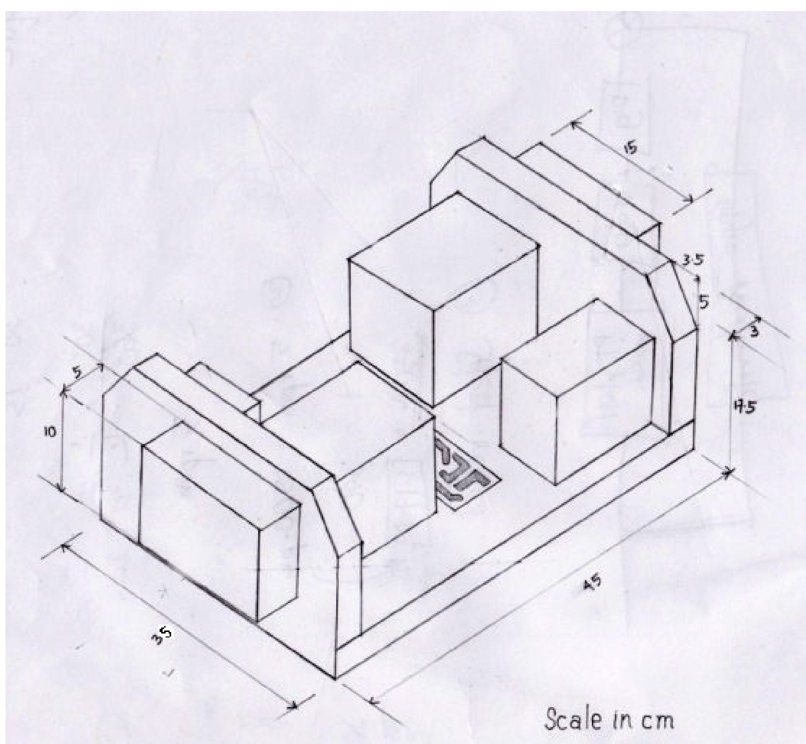

Figure 4.10: Detail Design with Dimensioning

CHAPTER 5
CONCLUSION

The self-balancing system in a personal transporter demonstrates a high technology and yet can be achieved for everyone to be able to learn the knowledge. The sensor use in this self-balancing system is mostly by using gyroscope sensor but author found out that by using combo gyroscope and accelerometer can give out similar performance but yet cost effectively. Lots of other model has been analyzed by the author, and few characteristics to make this project accomplished also had been notice. Benefits of a personal transporter such economically and green technology is a proof to show that it is something that we should learn and to be developed in this country. Overall this project is a successful as all phases are completed and the objective is accomplished for proposes the design of the self-balancing system. Thus the author hopes, continuity of spirit to contribute to the country will continue and new technology is to be discovered.

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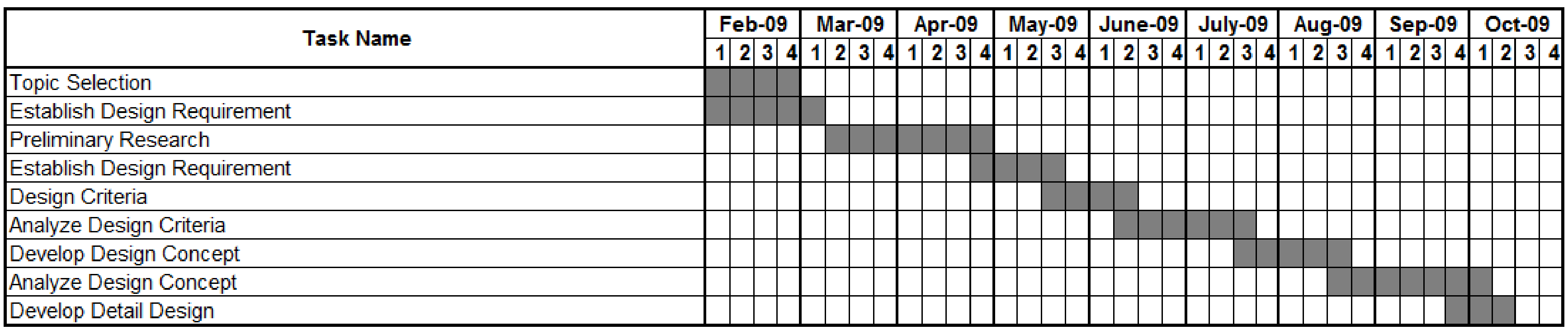
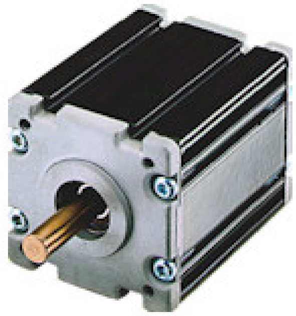


Appendix 1: Gantt chart

Appendix 2 – First Option:



Quantum NEMA 17 Brushless Servo Motors

Model No.		QB01701		
Motor Constants				
Stall Torque (continuous)	oz-in	21.6		
	Nm	0.15		
Max Rated Torque	oz-in	169		
	Nm	1.19		
Motor Constant	oz-in/√W	4.99		
	Nm/√W	0.035		
Elect. Time Constant	ms	0.520		
Mech. Time Constant	ms	1.670		
Thermal Resistance	°C/W	3.29		
Viscous Damping	oz-inRPM	1.5E-4		
	Nm/RPM	1.1E-6		
Cogging Torque (max.)	oz-in	1.5		
	Nm	1.1E-2		
Mechanical Constants				
Motor Inertia	oz-in-s^2	1.5E-2		
	kg-m^2	1.0E-4		
Motor Weight	oz	78.1		
	kg	2.24		
Poles	-	6		
Winding Constants				
Winding	-	A	B	C
Design Voltage	V	24	40	130
Peak Torque	oz-in	163	169	169
	Nm	1.15	1.19	1.19
Peak Current	A	81	65	40
Torque Constant (±10%)	oz-in/A	3.65	4.79	11.35
	Nm/A	0.026	0.034	0.080
No Load Speed	RPM	1722	2286	4665
	rad/s	180	240	488

Specifications on NEMA 17

Appendix 3 - Second Option:

Quantum NEMA 34 Brushless Servo Motor

Model No.		QB03401		
Motor Constants				
Stall Torque (continuous)	oz-in	33.5		
	Nm	0.23		
Max Rated Torque	oz-in	264		
	Nm	1.87		
Motor Constant	oz-in/√W	6.85		
	Nm/√W	0.048		
Elect. Time Constant	ms	0.590		
Mech. Time Constant	ms	1.330		
Thermal Resistance	°C/W	2.58		
Viscous Damping	oz-in/RPM	2.3E-4		
	Nm/RPM	1.6E-6		
Cogging Torque (max.)	oz-in	1.8		
	Nm	1.3E-2		
Mechanical Constants				
Motor Inertia	oz-in-s^2	2.2E-2		
	kg-m^2	1.5E-4		
Motor Weight	oz	103.3		
	kg	2.92		
Poles	-	6		
Winding Constants				
Winding	-	A	B	C
Design Voltage	V	24	40	130
Peak Torque	oz-in	219	264	264
	Nm	1.55	1.87	1.87
Peak Current	A	91	81	51
Torque Constant (±10%)	oz-in/A	5.13	6.32	16.20
	Nm/A	0.036	0.045	0.114
No Load Speed	RPM	1413	1913	3802
	rad/s	148	200	408
BEMF Constant (±10%)	V/kRPM	16.9	20.9	33.3
	V/rad/s	0.162	0.200	0.318
Terminal Resistance (±12%)	Ohms	0.26	0.40	1.03
Terminal Inductance (±30%)	mH	0.73	1.11	2.82

Specification on NEMA 34