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הפקולטה למדעי ההנדסה

המחלקה להנדסת חשמל ומחשבים

Faculty of Engineering Science

Dept. of Electrical and Computer Engineering

פרויקט הנדסי שנה ד'

Fourth Year Engineering Project

דו"ח מכין

Preliminary Design

טיסה וניווט אוטונומיים של רחפנים ללא מערכת איכון גלובלית

Autonomous flight and navigation of UAV without GPS

Project number:	**p-2016-001**		**מספר הפרויקט:**
Students (Name & ID):	Asaf Sarid 301465258 Ohad Cohen 200654606	301465258 אסף שריד 200654606 אוהד כהן	**סטודנטים (שם ו ת.ז.):**
Supervisors:	Prof. Guterman Hugo Zohar Ilan	פרופ' הוגו גוטרמן אילן זוהר	**מנחים:**
Sponsors:			**תומכים:**
Submitting date:	01/12/2015		**תאריך הגשה:**

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1. Abstract

Autonomous flight and navigation of UAV without GPS

Students: Asaf Sarid, Ohad Cohen
asafsari@post.bgu.ac.il

Supervisors: Prof. Guterman Hugo, Zohar Ilan

As part of the technological development, the unmanned air vehicles (UAVs) are taking a major portion of the world of aviation. In order to increase the functionality of the UAVs, there is need to improve existing systems and to add new abilities, allowing the UAVs to be used in variety of applications.
One of the most important abilities of an UAV is to navigate and move around in an autonomous manner, made possible using GPS. But when there is a problem in the GPS, the UAV cannot navigate properly and is unable to compensate drifting and other diversities caused by external disturbances.

The problem we aim to solve in our project is dealing with navigation in an outdoor environment while GPS is denied or disturbed, causing the basic autonomous navigation system to be nonfunctional.
We attend to deal with this problem by implementing a controller which allows the UAV to navigate from a known starting point to a given target point and avoiding obstacles. The content of our controller will be divided into two main parts. One sub unit that will receive data from external auxiliary sensors (camera \ ultrasonic \ laser) and estimate the movement and position of the UAV using build-in real-time algorithm and techniques. The other part converts the data from the first part to command for the internal flight controller in order to track the desired navigation path.

Key words: Technological development, UAV, aviation, navigation, autonomous flight, GPS, drift, adversity, outdoor environment, sensors, real-time algorithm.

<u>טיסה וניווט אוטונומיים של רחפנים ללא מערכת מיקום גלובלית</u>

סטודנטים: אסף שריד, אוהד כהן
asafsari@post.bgu.ac.il

מנחים: פרופ' גוטרמן הוגו, זוהר אילן

כחלק מההתקדמות הטכנולוגית, הולכים ותופסים הכלים האווירים הבלתי מאוישים (רחפנים) נתח נכבד מעולם התעופה. על מנת להגביר את הפונקציונליות של הרחפנים, יש לשפר מערכות קיימות ולהוסיף יכולות חדשות שיאפשרו לרחפנים לשמש במגוון רחב של יישומים. אחת מהיכולות החשובות ביותר ברחפן היא להתנייד בצורה עצמאית, יכולת המתאפשרת בעזרת מערכת מיקום גלובלית (ממ"ג). אך במידה וישנה בעיה בממ"ג הרחפן אינו יכול לנווט כראוי, ולא מתאפשר לו לפצות על סחיפה או שגיאות אחרות הנגרמות מהפרעות חיצוניות.

הבעיה שאנחנו מתכננים לפתור בפרויקט היא התמודדות עם ניווט בסביבה חיצונית בזמן תקלה או הפרעה בממ"ג, הגורמים למערכת הניווט האוטונומית הבסיסית לחוסר תפקוד. אנו מתכננים להתמודד עם בעיה זו על ידי מימוש בקר המאפשר לרחפן לנווט את דרכו מנקודת פתיחה לנקודת יעד ידועה מראש והימנעות ממכשולים. הבקר יורכב משני חלקים עיקריים, חלק ראשון יקבל מידע מחיישני עזר חיצוניים (מצלמה \ אולטרסוניק \ לייזר) וישערך את תנועת ומיקום הרחפן בעזרת טכניקות ואלגוריתמים מובנים בזמן אמת. החלק השני, ימיר את המידע מהחלק הראשון לפקודות עבור בקר הטיסה הפנימי במטרה לעקוב אחרי נתיב הניווט הרצוי.

מילות מפתח: התפתחות טכנולוגית, רחפן, תעופה, ניווט, טיסה עצמאית, מערכת מיקום גלובלילת, סחיפה, שגיאה, סביבה חיצונית, חיישנים, אלגוריתמים, זמן-אמת.

2. Project Goals

We can describe our project goals by one main goal and two sub goals that are derived from the main goal. Our main goal is to build an UAV that will be able to navigate to a given point without using a GPS. We can divide this main goal into two sub goals. First, we will need to create and implement a navigation controller that does not use a GPS and that will navigate the UAV to a given point with no more than 25 meter radius deviation for a 1 km flight. Second, we will need to design the UAV itself and its flight controller in a way that it will be able to avoid obstacles autonomously. The measure of success for this sub goal will be by avoiding large obstacles such as building or large trees.

3. Spec Sheet

Development of a system that will allow an UAV to navigate autonomously to a specific location without using a GPS. The final product will be an UAV (with build-in flight controller and IMU) equipped with a camera, sensors and controller that will navigate itself to a specific location without using any external systems.

We will implement a controller that will be configured by the user to set the desired coordinates. During the flight it will receive pictures in a specific frame rate from a camera located on the bottom of the UAV. By using Optical Flow technique, we will be able to compute the position, velocity, acceleration and direction of the UAV and by that we will be able to keep the UAV on the desired path within minimum deviation.

One of the most important advantages of this technique is that it’s very accurate comparing to other techniques that does not use GPS. Any aircraft has drifts during the flight that creates cumulative error, and the gyroscopes and accelerometers also have deviation from the real velocity. Optical Flow technique will help us to minimize this error. The algorithm will analyze the data from the pictures string and will use it to give the right orders to the motors.

The future applications of this product can be commercial transportation or for military uses for example.

4. Literature survey

4.1. General Definitions

- UAV- (Unmanned Aerial Vehicle) Is an aircraft with no pilot on board. UAVs can be remote controlled aircraft (e.g. flown by a pilot at a ground control station) or can fly autonomously based on pre-programmed flight plans or more complex dynamic automation systems. [1]
- PID (Proportional, Integrative, Derivative) - This is the most well-known family of controllers, best fit LTI (Linear Time Invariant) systems. (The usage and advantages/disadvantages will be discussed later in this chapter).
- IMU (Inertial Measurement Unit) - Is an electronic device that measures and reports a body's specific force, angular rate, and sometimes the magnetic field surrounding the body, using a combination of accelerometers and gyroscopes, sometimes also magnetometers. [2]
- SLAM (Simultaneous Localization and Mapping) - Is the computational problem of constructing or updating a map of an unknown environment while simultaneously keeping track of an agent's location within it. [3]
- Euler angles- The Euler angles are three angles introduced by Leonhard Euler to describe the orientation of a rigid body (The body frame). The body frame axes are aligned with the sensors, while the inertial frame axes are Earth-fixed. [4]
- Optical Flow- The change of structured light in the image, e.g. on the retina or the camera’s sensor, due to a relative motion between the eyeball or camera and the scene. [5].

4.2. Quadrotor Basics

4.2.1. Rigid Body and UAV Dynamics

In order to understand how the UAV response to rotation of the motors, we need to develop system (definitions and equations) that will receive the speed of the 4 motors of our UAV, and the output is the movement of the body-center of mass motion for example. The quadrotor dynamics modeling process the incoming parameters and values, and outputs the behavior of the body. For example, to know the angles in the body frame (Euler angles) of the quadrotor (pitch, roll and yaw), and these angles states the transition of the body in the space. When going deeper into the mathematical aspect, we can notice that the angles of the body influence the velocity of the body, but not vice versa. In addition, one of the main challenges is to transfer from body frame to inertial frame coordinate systems in both directions, using transformation matrixes. There are three basics equations that determine the total torque in each angle: [6]

$$\tau = r \times F \tag{1}$$

$$\text{Pitch: } \tau_{b_1} = d(f_2 - f_4) \tag{2}$$

$$\text{Roll: } \tau_{b_2} = d(f_3 - f_1) \tag{3}$$

$$\text{Yaw: } \tau_{b_3} = -\tau_1 + \tau_2 - \tau_3 + \tau_4 \tag{4}$$

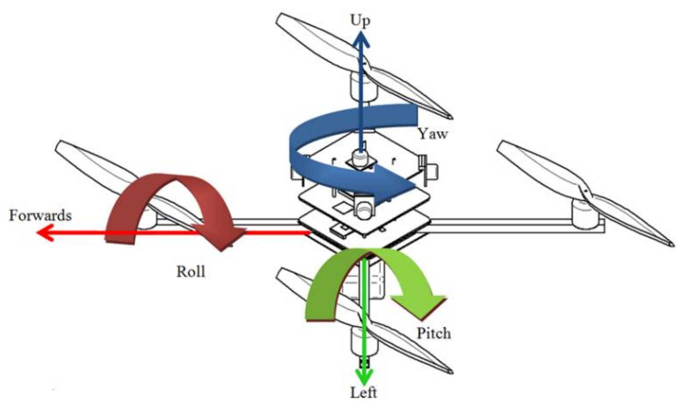


Figure 1- Euler angles [7]

The velocity in the X-Y surface of the body derivate from these angles.

4.2.2. Flight Controller

Every UAV must have internal flight controller, in order to maintain stable flight. The controller receives commands from the user- desired pitch, roll, yaw angles and thrust (altitude). Those parameters being processed by the controller, resulting in output speed of the 4 motors of the UAV. Controlling the UAV can be achieved only if we are able to measure the real angles of the UAV, we do so by the Inertial Measurement Unit (IMU). The controller integrate feedback from the IMU and input from the user to process the next output command. There are many designing flight controller methods- linear, non-linear

and visual feedback are the most common methods. For example: PID controller, LQR controller, and H infinity controller. [6][8]
The internal sensors in the IMU produce the real position and movement of the UAV, but each type of sensor has its own disadvantages. The accelerometer sense all the forces working on the body, not just the gravity vector. Meaning that this data is reliable only on long term. The gyroscopes problem, on the contrary, is increasing error over time, because that is integration, the measurement tends to drift, so this data is more reliable on short term. The solutions to these diversities is to combine them together, resulting in more accurate measurement. The combining can be achieved by complementary filter for example, or by multiplexing the source of the data in some rate. [6][8]

4.3. GPS Denied Navigation Methods

4.3.1. Theater Positioning System (TPS)

Theater Positioning System (TPS) is a positioning method that can perform in GPS-denied environments and can work with, or independently of, GPS systems [11]. This method is widely used as a backup to GPS in military. One of the main problem of this method is its accuracy. Unlike GPS, the errors in TPS are harder to capture and difficult to be approximated by an exact model. This method is mostly use as a backup for GPS and cannot replace it. In addition, this method is used mostly for ground object, and for these reason it won’t be used on UAV as a main navigation system.

4.3.2. Simultaneous Localization and Mapping (SLAM)

Simultaneous Localization and Mapping (SLAM) is concerned with the problem of building a map of an unknown environment by a mobile robot while at the same time navigating the environment using the map [12]. SLAM consists of multiple parts; Landmark extraction, data association, state estimation, state update and landmark update. Some methods for navigation today uses SLAM with Kalman Filter [13].

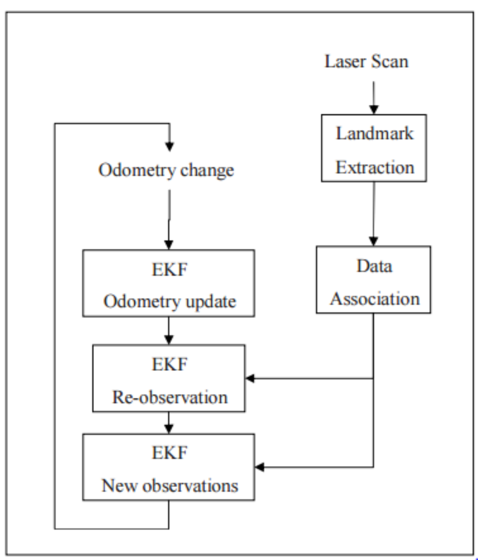


Figure 2 – Overview of the SLAM process [12]

4.3.3. Optical Flow (OF)

Optical Flow (OF) is the method we chose to use and implement in our project. There are few methods for motion estimation using optical flow. The methods try to calculate the motion between two image frames which are taken at time t and $t+\Delta t$ at every voxel position. These methods are called differential since they are based on local Taylor series approximations of the image signal [5].
For a 2D dimensional case let $I(x,y,t)$ be the intensity of the voxel at location(x,y). If we assume that the movement is small and the time difference between two images is small we get:

$$I(x,y,t) = I(x+\Delta x, y+\Delta y, t+\Delta t) \tag{5}$$
$$I(x,y,t) + I_x\Delta x + I_y\Delta y + I_t\Delta t = I(x+\Delta x, y+\Delta y, t+\Delta t) \tag{6}$$

From these two equations we get

$$I_xV_x + I_yV_y = -I_t \tag{7}$$

This equation is known as the aperture problem, that in order to get (V_x, V_y) we need to assume additional constrains. [10]
There are two main differential methods that solve this equation using some additional constrains: Lucas-Kanade and Horn-Schunck. The difference between those two are about what they assume in order to solve the basic equation above. Horn-Schunck algorithm assumes smoothness in the flow over the whole image. While Lucas-Kanade assumes that flow is essentially constant in a local neighborhood of the pixel under consideration and solves the basic optical flow equations for all the pixels in that neighborhood, by the least squares criterion [5]. The Lucas-Kanade method is more widespread and shows acceptable computational burden and better performance than other methods [14].
An optical flow sensor is a vision sensor capable of measuring optical flow or visual motion and outputting a measurement based on optical flow. Optical flow sensors can be used, as well, in UAVs for obstacle avoidance.
There are two main models of optical flow sensors. The first is PX4FLOW, uses Lucas-Kanade method on a 4x4 binned and cropped area at 400Hz. The other type is mouse sensors such as ADNS3080 for example that uses Horn-Schunck method. The PX4FLOW has some advantages over mouse sensors as it has a very high light sensitivity and that it uses Lucas-Kanade method that [14] shows it gives better performance than Horn-Schunck method.
We can see in [14] that optical flow method was implemented on an UAV, and was tested. They tested both static position hold and autonomous flight plan. The flight plans were no more than 2 meters from each waypoint, and the maximal final error measured was 45cm.

5. Design proposal

5.1. Flow Chart

In order to achieve our main goal we will need to execute the following steps:

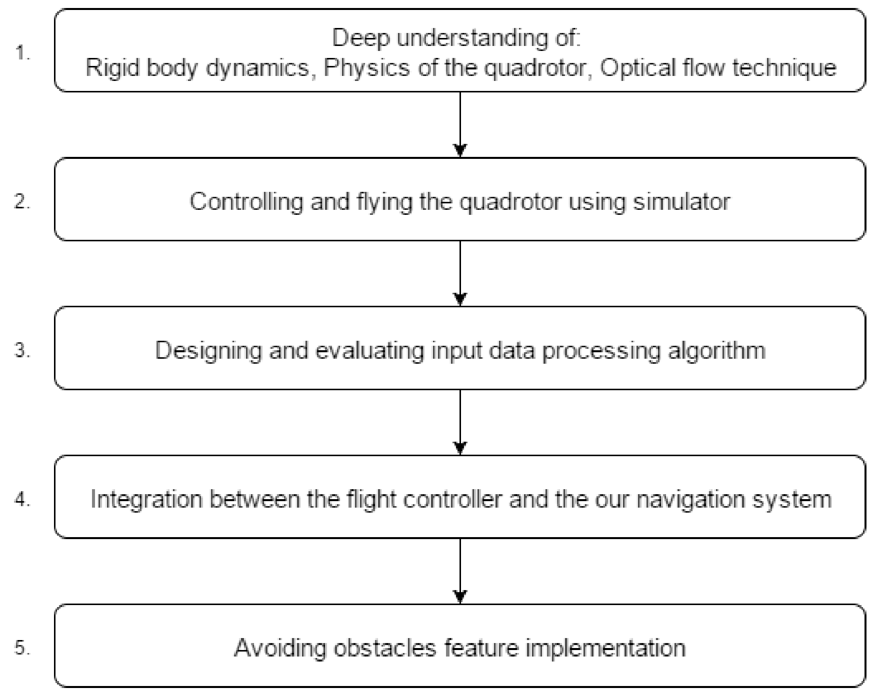


Figure 3 – Design flow chart

1. At first, we need to understand the physics and dynamics of a quadrotor model and in order to implement a navigation system we need to understand the GPS-denied navigation techniques.
2. This step will help us understand the controlling of a quadrotor and the effect of some flight parameters by changing them in the simulators [6].
3. Implementation of the GPS-Denied navigation system using Optical Flow technique. This module will receive input from the sensors and estimate the movement and position of the quadrotor. First on a static system, with only a camera and a computer and only then implementing it on a controller that will be connected to the quadrotor.
4. Creating a top level unit, converting the data that we received from the first part and the feedback from the flight controller into commands for the flight controller. The inputs to this part forms the complete state of the UAV.
5. Implementing and inserting a feature that will handle obstacles on its navigation path.

5.2.System Block Diagram

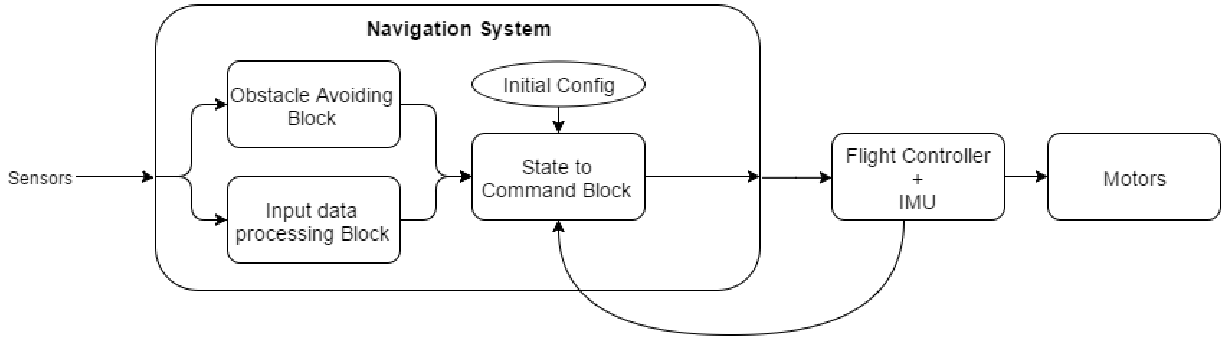


Figure 4- General Block Diagram

5.3. Project Design Constrains

Our solution for the problem should be able to handle few unique constrains, most of them derives from the fact that our design supposed to function well in outdoor environment.
The disadvantages are that first, the drifting error can increase rapidly due to wind or other external forces. Second, we can rely only on the surface beneath us for navigating unlike indoor navigation. In addition, the distance from the ground is not constant, which influence our navigation algorithm (depends on externals sensors).
The positive aspects of this constrains are first, we might be able to use GPS for limited quanta once in a while to fix our total error. Second, we can fly the UAV in relatively high speed without to be concerned of damage for the UAV.

6. Project Content Definition

The project content is a navigation controller. The controller can be added to any UAV with basic flight controller that uses IMU, and maintain stable flight from known starting point to given target point. The interface of the controller will receive inputs from the external sensors and the built-in flight controller and its outputs are commands for the flight controller.

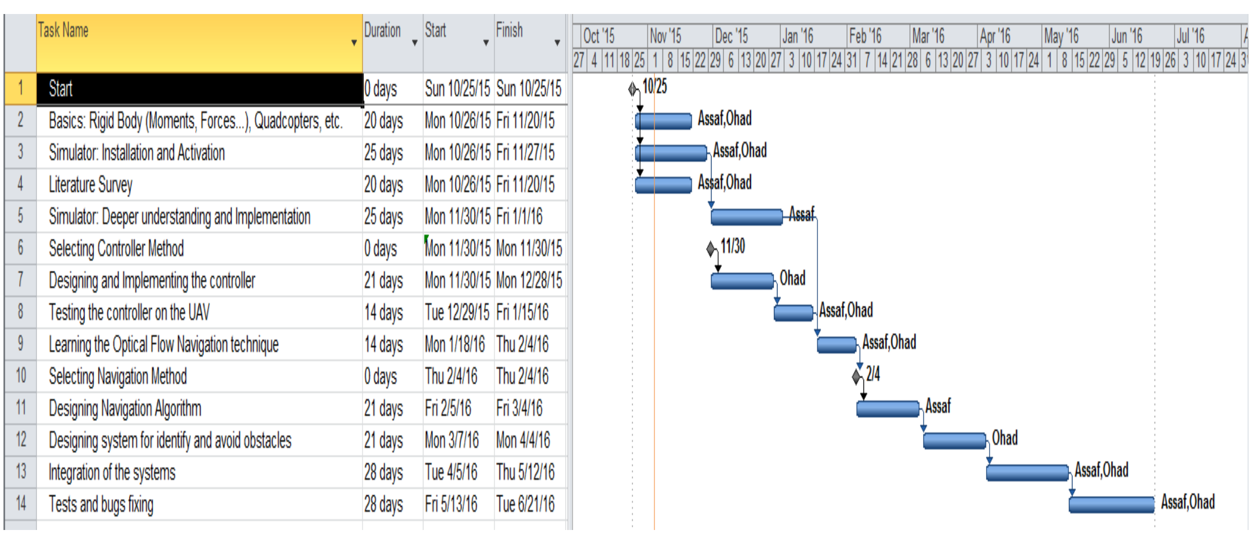
7. Final Testing Procedure Proposal

The final test procedure will be a flight experiment. The flight controller will know its starting point, and we will give it the destination point (by distance and angle). A successful experiment is defined by reaching the destination point by a radius of 25 meter for a 1 km flight distance. At first we will test it without obstacles, and the last final test will be with including at least one obstacle in its flight path.

8. Budget

Supplies			
Component	Price	Description	Total
Quadcopter	400$ X 2	S500	800$
Controller	100$ X 2		200$
Camera	150$ X 2	PX4FLOW	300$
Sensors	20$ X 6		120$
Prints	50$		50$
Total Supplies			1470$
HR			
Name	Number of Hours	Hourly Salary	Total
Zohar Ilan	52 (2 * 26)	80$	4160$
Sarid Asaf	800 (65*10 + 150)	12$	960$
Cohen Ohad	800 (65*10 + 150)	12$	960$
Reserves (15%)			912%
Total HR			6992$
Total			**8462$**

9. Gantt



	Task Name	Duration	Start	Finish
1	Start	0 days	Sun 10/25/15	Sun 10/25/15
2	Basics: Rigid Body (Moments, Forces...), Quadcopters, etc.	20 days	Mon 10/26/15	Fri 11/20/15
3	Simulator: Installation and Activation	25 days	Mon 10/26/15	Fri 11/27/15
4	Literature Survey	20 days	Mon 10/26/15	Fri 11/20/15
5	Simulator: Deeper understanding and Implementation	25 days	Mon 11/30/15	Fri 1/1/16
6	Selecting Controller Method	0 days	Mon 11/30/15	Mon 11/30/15
7	Designing and Implementing the controller	21 days	Mon 11/30/15	Mon 12/28/15
8	Testing the controller on the UAV	14 days	Tue 12/29/15	Fri 1/15/16
9	Learning the Optical Flow Navigation technique	14 days	Mon 1/18/16	Thu 2/4/16
10	Selecting Navigation Method	0 days	Thu 2/4/16	Thu 2/4/16
11	Designing Navigation Algorithm	21 days	Fri 2/5/16	Fri 3/4/16
12	Designing system for identify and avoid obstacles	21 days	Mon 3/7/16	Mon 4/4/16
13	Integration of the systems	28 days	Tue 4/5/16	Thu 5/12/16
14	Tests and bugs fixing	28 days	Fri 5/13/16	Tue 6/21/16

10. References

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11. Appendix

11.1. Gantt Table

#	Start Date	End Date	Start Time	End Time	Cohen Ohad	Sarid Asaf	Task	Status	Adviser Approve	Adviser Notes
1	25/10.	20/11			☑ Time Clock	☑ Time Clock	Basics: Rigid Body, QuadCopter, etc.	In Progress	☐	
2	26/10.	27/11			☑ Time Clock	☑ Time Clock	Simulator: Installation and	In Progress	☐	
3	26/10.	20/11			☑ Time Clock	☑ Time Clock	Literature Survey	In Progress	☐	
4	30/11.	01/01			☐ Time Clock	☑ Time Clock	Simulator: Deeper Understanding and	Not Done	☐	
5	30/11.	28/12			☑ Time Clock	☐ Time Clock	Designing and Implementing the	Not Done	☐	
6	29/12.	15/01			☑ Time Clock	☑ Time Clock	Testing the controller on the UAV	Not Done	☐	
7	18/01.	04/02			☑ Time Clock	☑ Time Clock	Learning Optical Flow navigation technique	Not Done	☐	
8	5/02/2	04/03			☐ Time Clock	☑ Time Clock	Designing navigation algorithm	Not Done	☐	
9	7/03/2	04/04			☑ Time Clock	☐ Time Clock	Designing system for identifying and	Not Done	☐	
10	5/04/2	12/05			☑ Time Clock	☑ Time Clock	Integration of the systems	Not Done	☐	
11	13/05.	21/06			☑ Time Clock	☑ Time Clock	Tests and bug fixing	Not Done	☐	

11.2. Grading

המלצת ציון לדו"ח מכין

<u>אם יש צורך, לכל סטודנט/ית בנפרד</u>

מספר הפרויקט: P-20____-______

שם הפרויקט:

שם המנחה החיצוני:

שם המנחה מהמחלקה:

שם הסטודנט/ית: ת.ז.:

%		חלש 64-55	בינוני 65-74	טוב 84-75	ט"מ 94-85	מצוין 100-95	
15	הבנת הנושא הצורך וסביבת היישום						
15	חיפוש מקורות והבנת עבודות דומות						
15	שלמות דף מפרט (הצעת מחקר)						
15	הצעת תכנון ותכנון הבדיקות הסופיות						
10	גילוי יוזמה וחריצות						
20	פתרון בעיות, מקוריות ותרומה אישית (מעבר למילוי ההנחיות)						
10	הערכת תקציב, לו"ז וחלוקת עבודה, ציון מקורות ושלמות כללית						

הערכת רמת הקושי של הפרויקט: קל מאוד / קל / בינוני / קשה / קשה מאוד

הערות: