פרויקט נופר 69131

Vision-based UAV (Unmanned aerial vehicle) navigation

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מוצג לחזי עתיר בוחן מטעם המדען הראשי במסגרת תוכנית נופר

Abstract

In the presentation described algorithms for Vision-based UAV (Unmanned aerial vehicle) control and navigation developed in Ariel University during Nofar project.

Lab drone flight

החדשנות 1

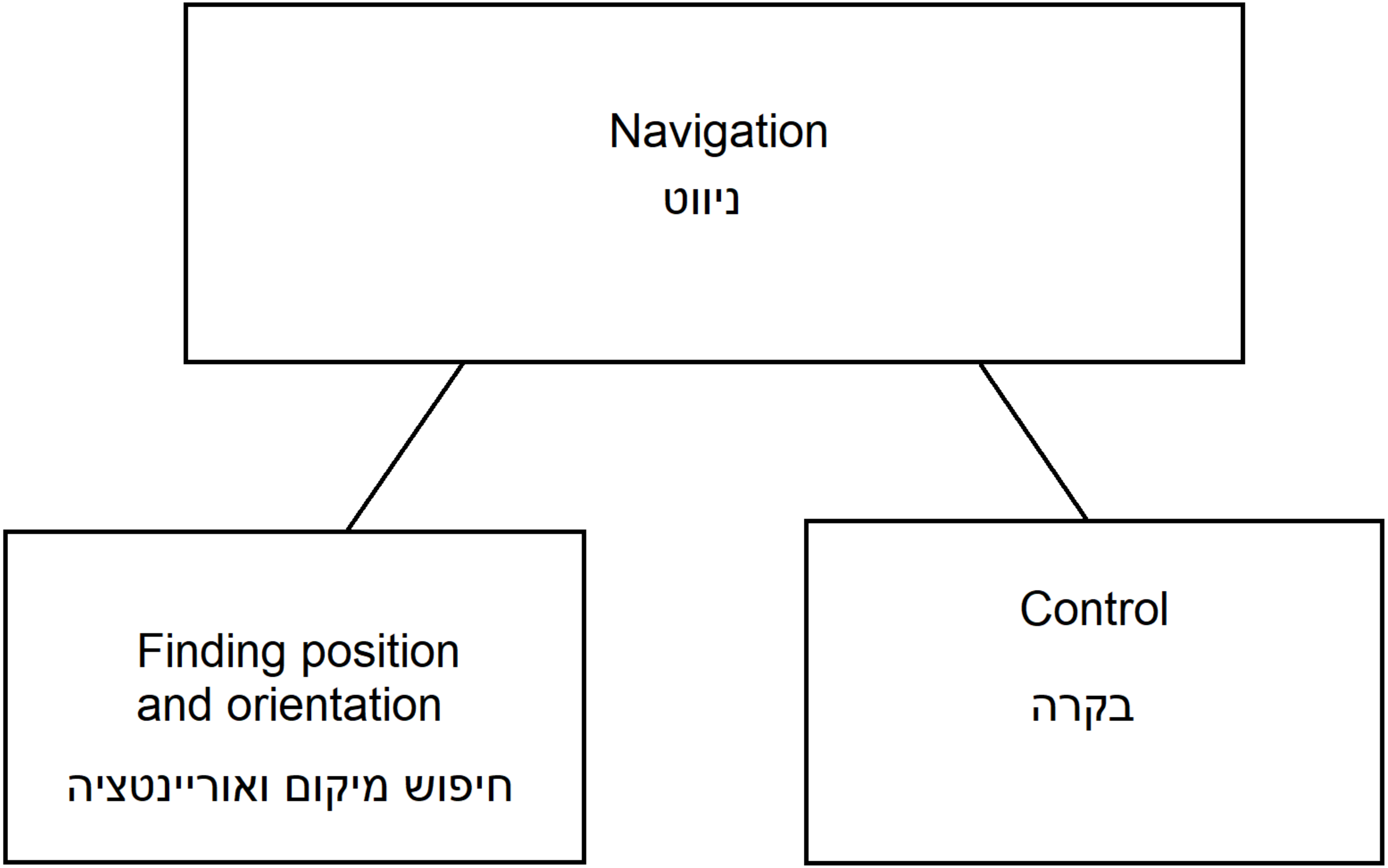
רקע טכנולוגי

Currently used GPS/INS methods are not trusty and are not noise-immune (easily suppressed) enough.

So, we plan to use vision-based navigation.

Contrary to the similar projects, we plan to use a big set of existing and new methods that allow us to get universality of our system – the system will operate in different complex environments for different optical systems with precision enough for successful drone navigation.

Navigation ניווט



Navigation

ניווט

Finding position and orientation

חיפוש מיקום ואוריינטציה

Control

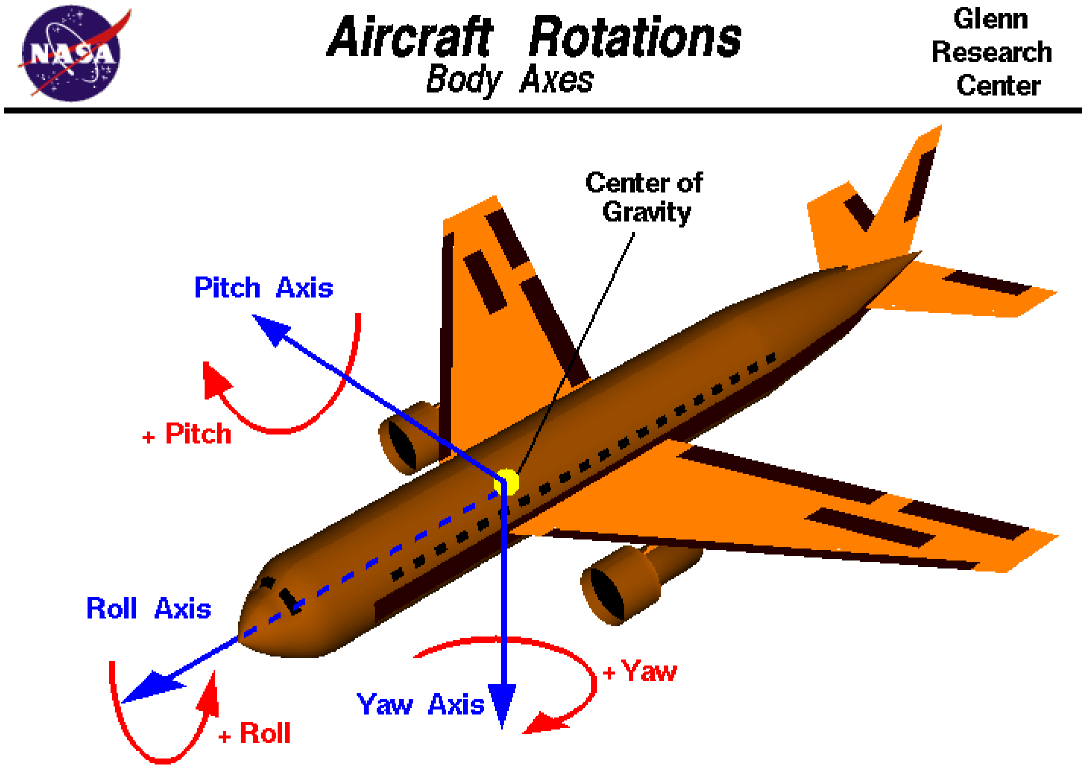
בקרה

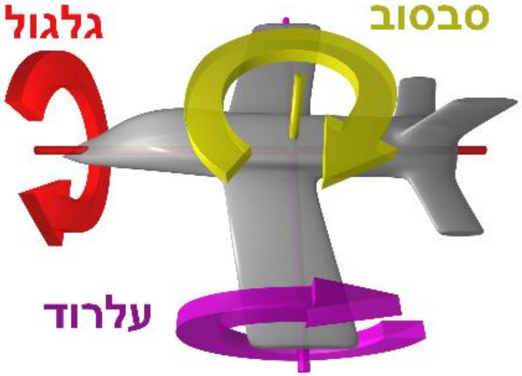
Coordinates and Euler angles
מיקום וזוויות אוילר

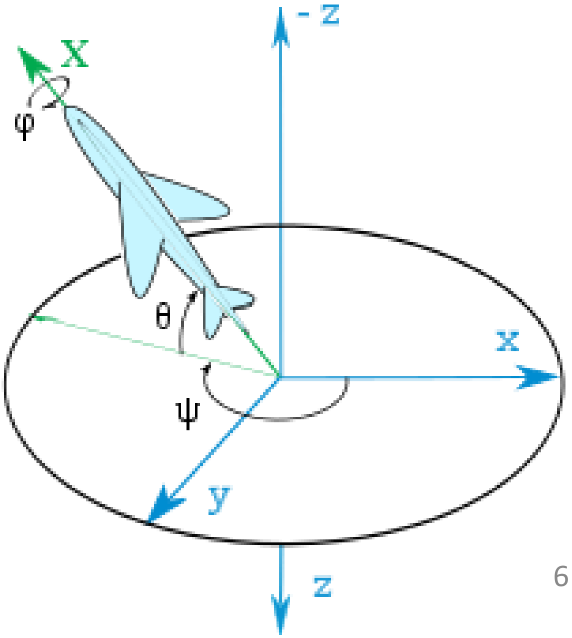
סיבוב(3 מימדים)+הזזה(3 מימדים) =6D

סיבוב מטוס:

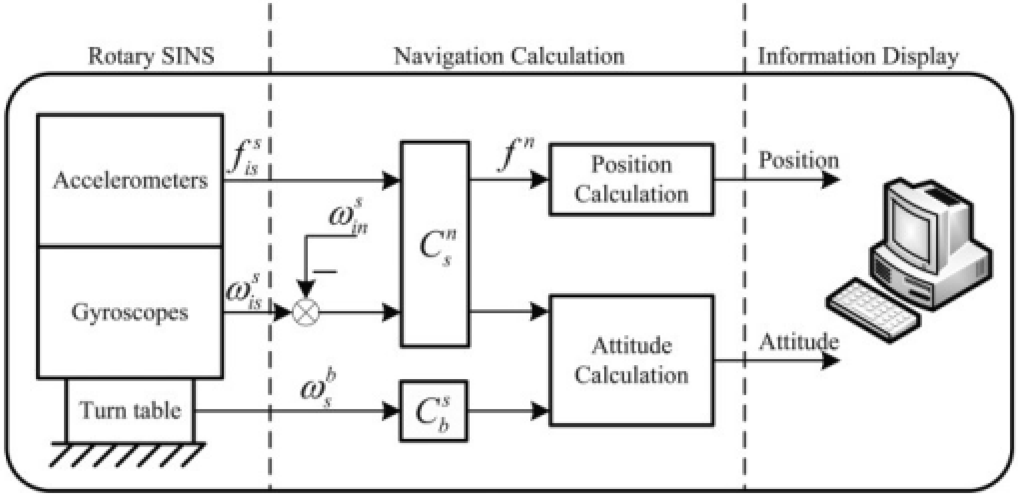
צירי גוף

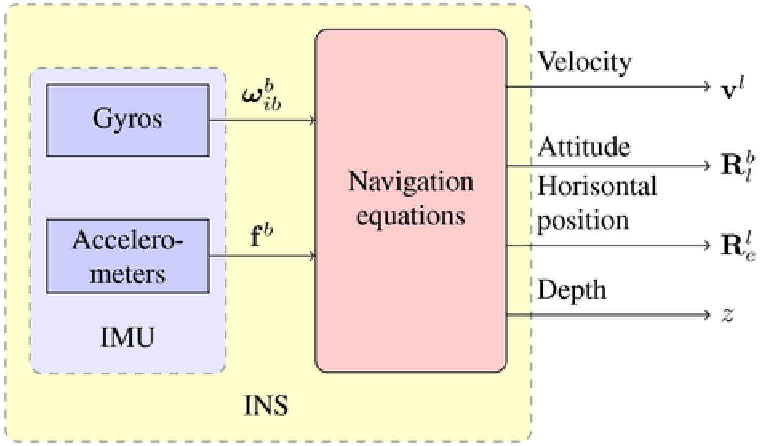




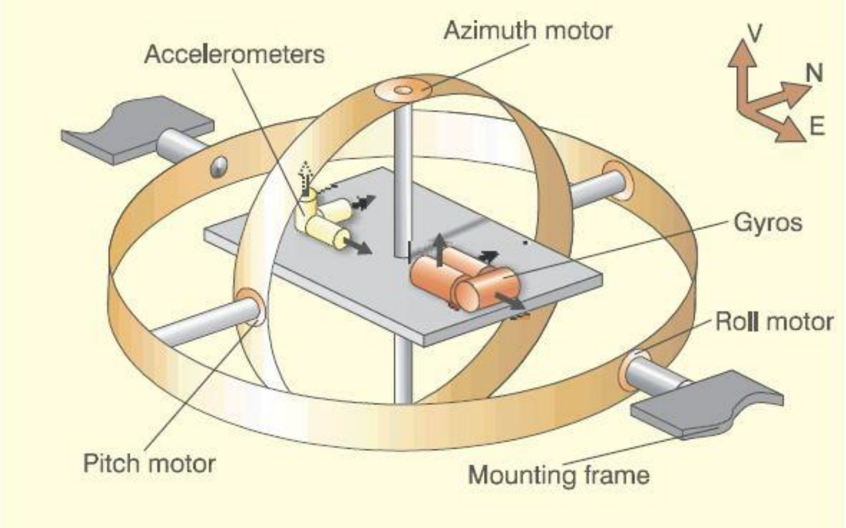


inertial navigation ניווט אינרציאלי



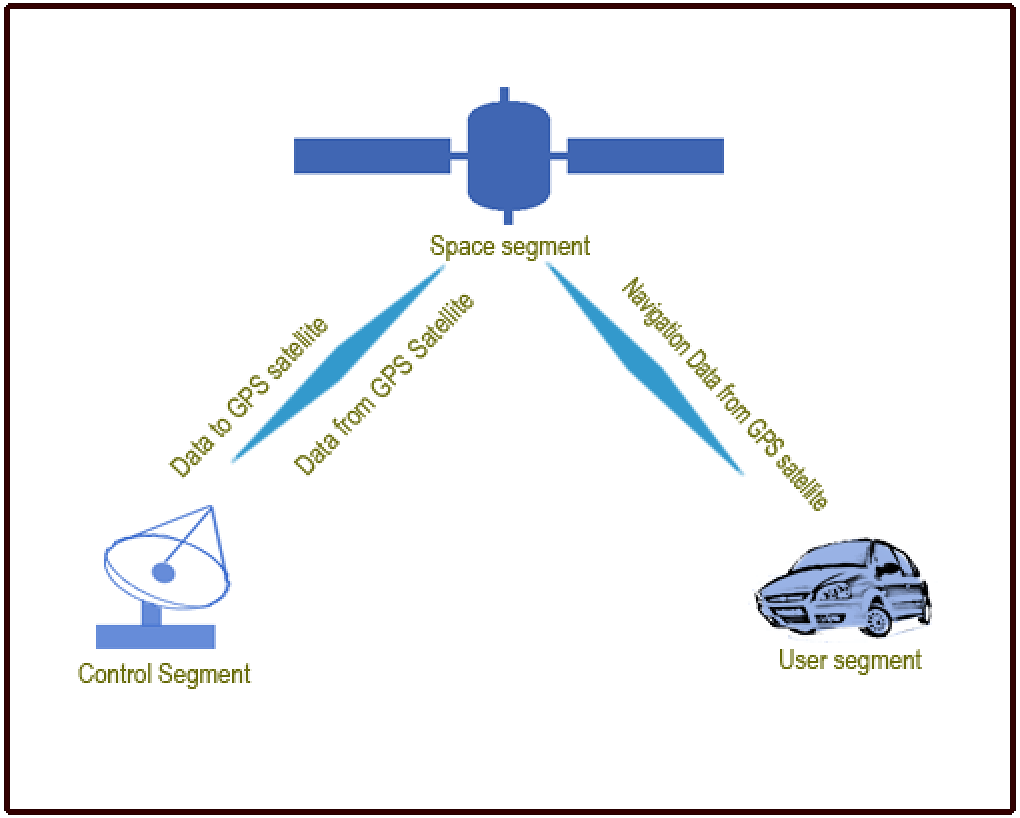


Inertial navigation systems (INS) use a combination of accelerometers and angular rate sensors (gyroscopes) to detect altitude, location, and motion

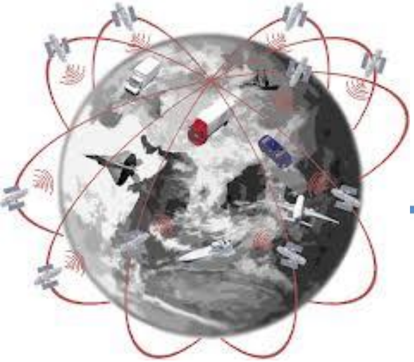


מערכת ניווט אינרציאלית כוללת גירוסקופ למדידת כיוון ומד תאוצה למדידת מרחק

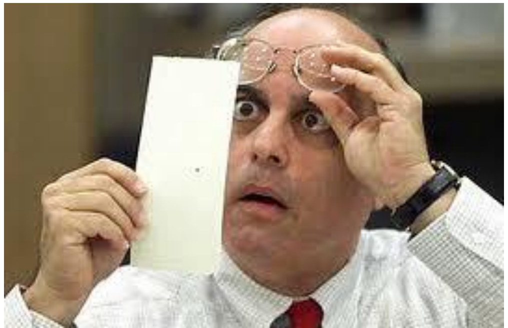
מערכת מיקום גלובלית (ממ"ג) GPS



Problems №1- בעיה ראשונה



- GPS/INS - שטה שגרתית
- GPS – no autonomy and noise sensitivity
- לא אוטונומי ורגישה לרעש
- INS – increasing error
- שגיאה גוררת
- What to do?



Solution -Vision-based navigation

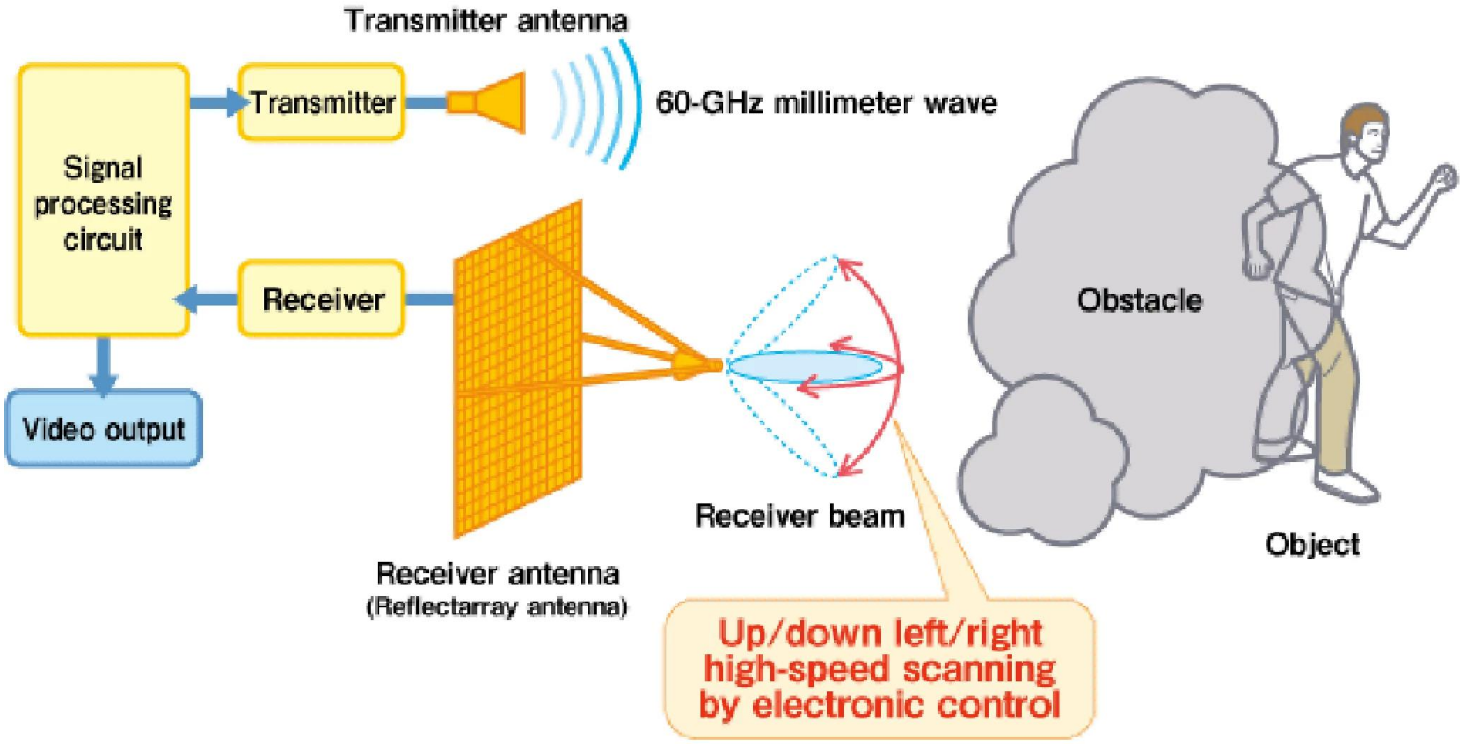
פתרון: ניווט מבוסס ראיה ממוחשבת דומה לניווט אנושי בעזרת ראיה

- Vision-based navigation – similar to the human navigation by eyes

Millimeter-wave TV camera sees through smoke, fog and even walls (the need 1)

המצלמה רואה דרך עשן, ערפל ואפילו קירות

https://newatlas.com/nhk-millimeter-wave-tv-camera/15411/



Ability to monitor large areas in complete darkness, glaring light, and adverse weather (the need 1)

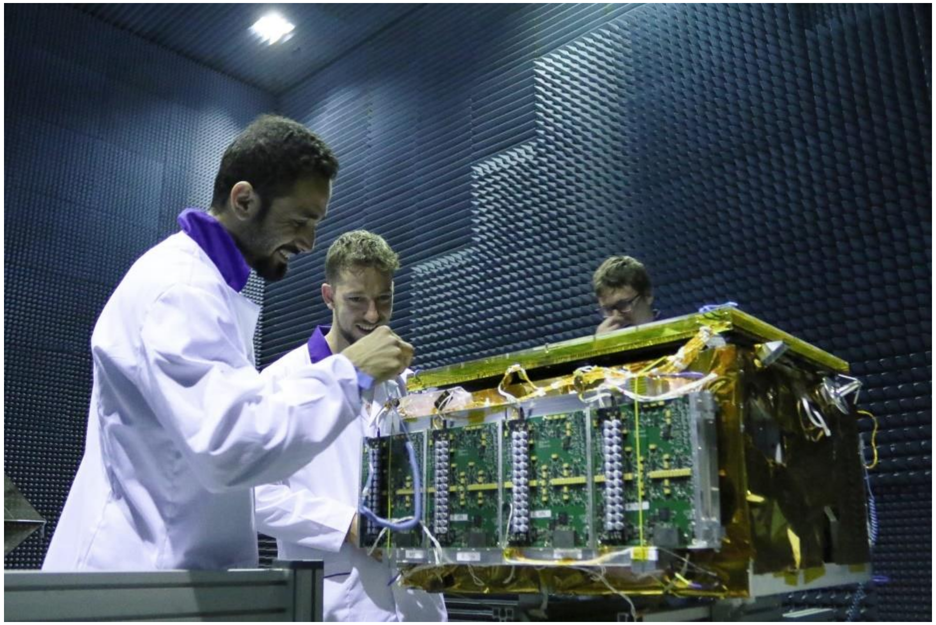
באור בוהק ובמזג אוויר שלילי, בחושך מוחלט

https://www.flir.eu/products/flir-elara-dx-series/

Satellites that can see through clouds (the need 1)

https://www.cnbc.com/2017/12/01/iceye-will-launch-satellites-that-can-see-through-clouds-in-january.html

The company uses synthetic aperture radar (SAR) to provide real-time imagery even at night or through cloud cover.



Event cameras – very high dynamic range, no motion blur, and a delay in the order of microseconds

file:///C:/fff/JOB/An_End-to-End_Broad_Learning_System_for_Event-Base.pdf

https://rpg.ifi.uzh.ch/research_dvs.html

Event cameras are bio-inspired vision sensors measuring brightness changes (referred to as an ‘event’) for each pixel independently, instead of capturing brightness images at a fixed rate using conventional cameras. The term ‘event’ refers to an output spike, characterized by a specific spatial location (x, y), timestamp (t) and brightness change polarity (p), shown in Fig. 1.

Dynamic range - ratio between brightest and darkest of image

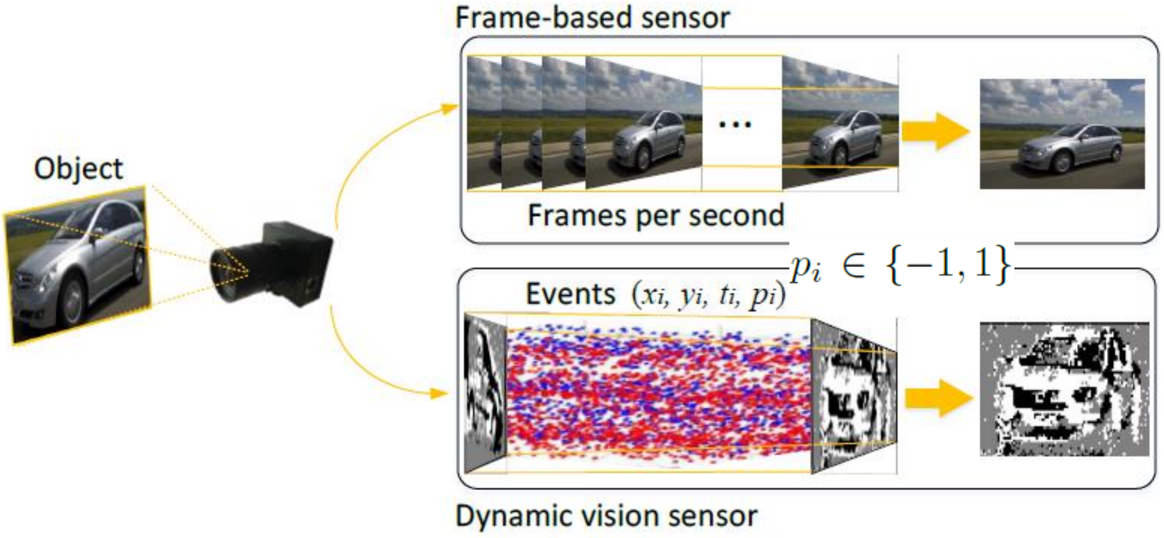


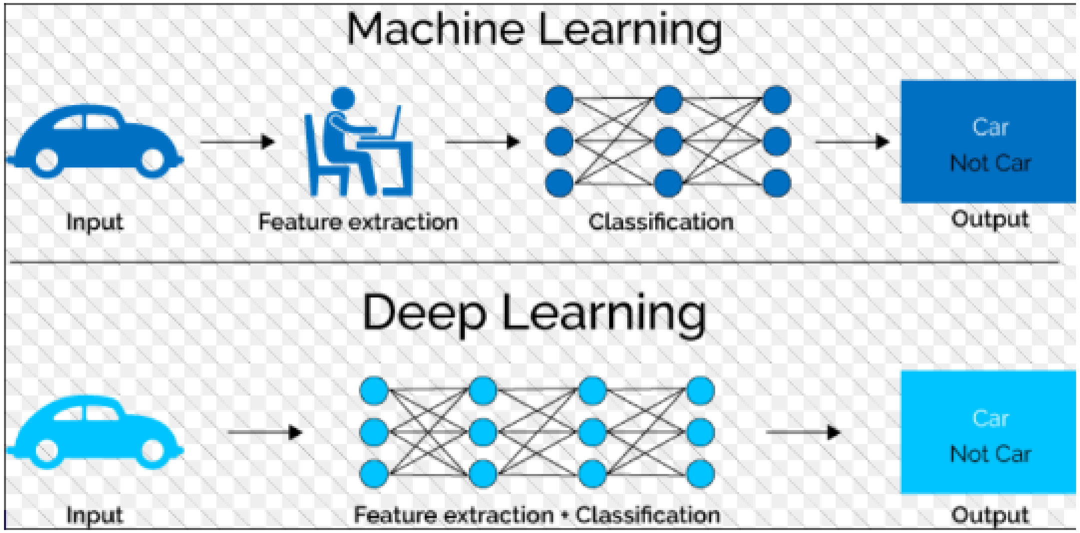
FIGURE 1: Difference between frame-based camera and the event-based camera.

הטכנולוגיה המוצעת

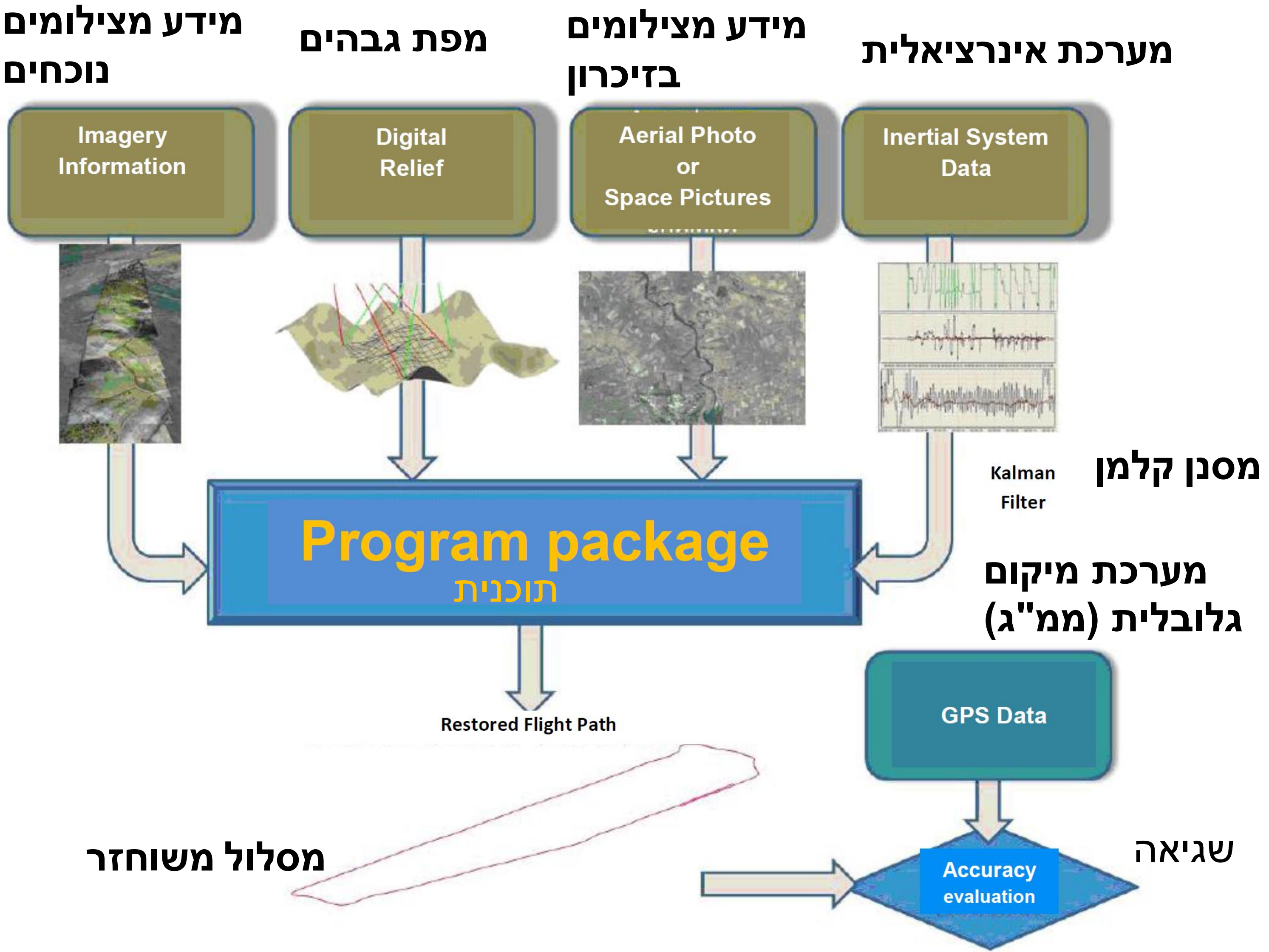
רקע טכנולוגי – מדוע הטכנולוגיה צפויה לעבוד?!

New Technologies

Following the availability of the following technologies



3 methods of VBN



מידע מצילומים נוכחים

Imagery Information

מפת גבהים

Digital Relief

מידע מצילומים בזיכרון

Aerial Photo or Space Pictures

מערכת אינרציאלית

Inertial System Data

Kalman Filter

מסנן קלמן

Program package

תוכנית

מערכת מיקום גלובלית (ממ"ג)

GPS Data

Restored Flight Path

מסלול משוחזר

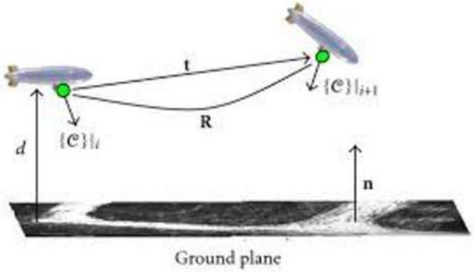
Accuracy evaluation

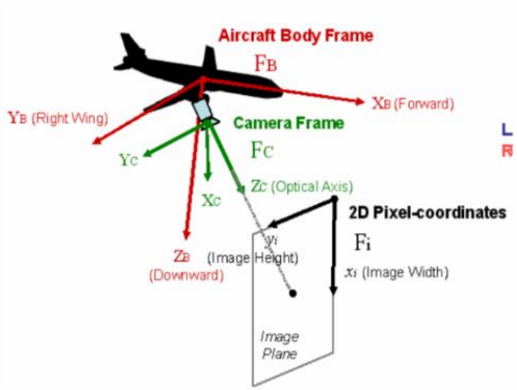
שגיאה

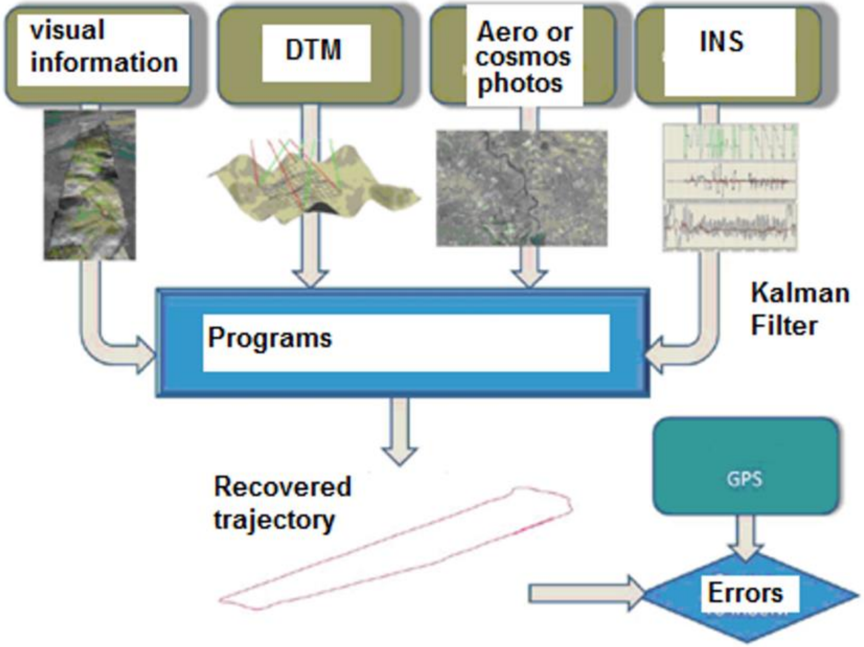
ARIEL UNIVERSITY

Scheme of visual navigation

3 methods of VBN







visual information

DTM

Aero or cosmos photos

INS

Programs

Kalman Filter

Recovered trajectory

GPS

Errors

Figure 1. In the picture at the top left, we show how a single camera on a drone is used in two positions, allowing you to create the effect of stereovision even with only one camera.

In the picture at the down left, we show how the coordinate systems of the aircraft and the on-board camera looking down are set.

In the picture at the right, we show the structure of the operation of the video-navigation system, which uses three methods described in the text: data into the video-navigation program comes from the on-board camera (**visual information**), from the computer memory comes a priori known relief elevation map (**Digital Terrain Map - DTM**), from the computer memory comes a priori known images of the terrain (**Aero or cosmos photos**). In addition, video-navigation data is combined with data from the Inertial Navigation System (**INS**) using **Kalman filter**. The trajectory recovered (**Recovered trajectory**) using the video-navigation program (**Programs**) is compared with the trajectory obtained using Satellite Navigation (**GPS**) to find errors (**Errors**) and check the quality of video-navigation.

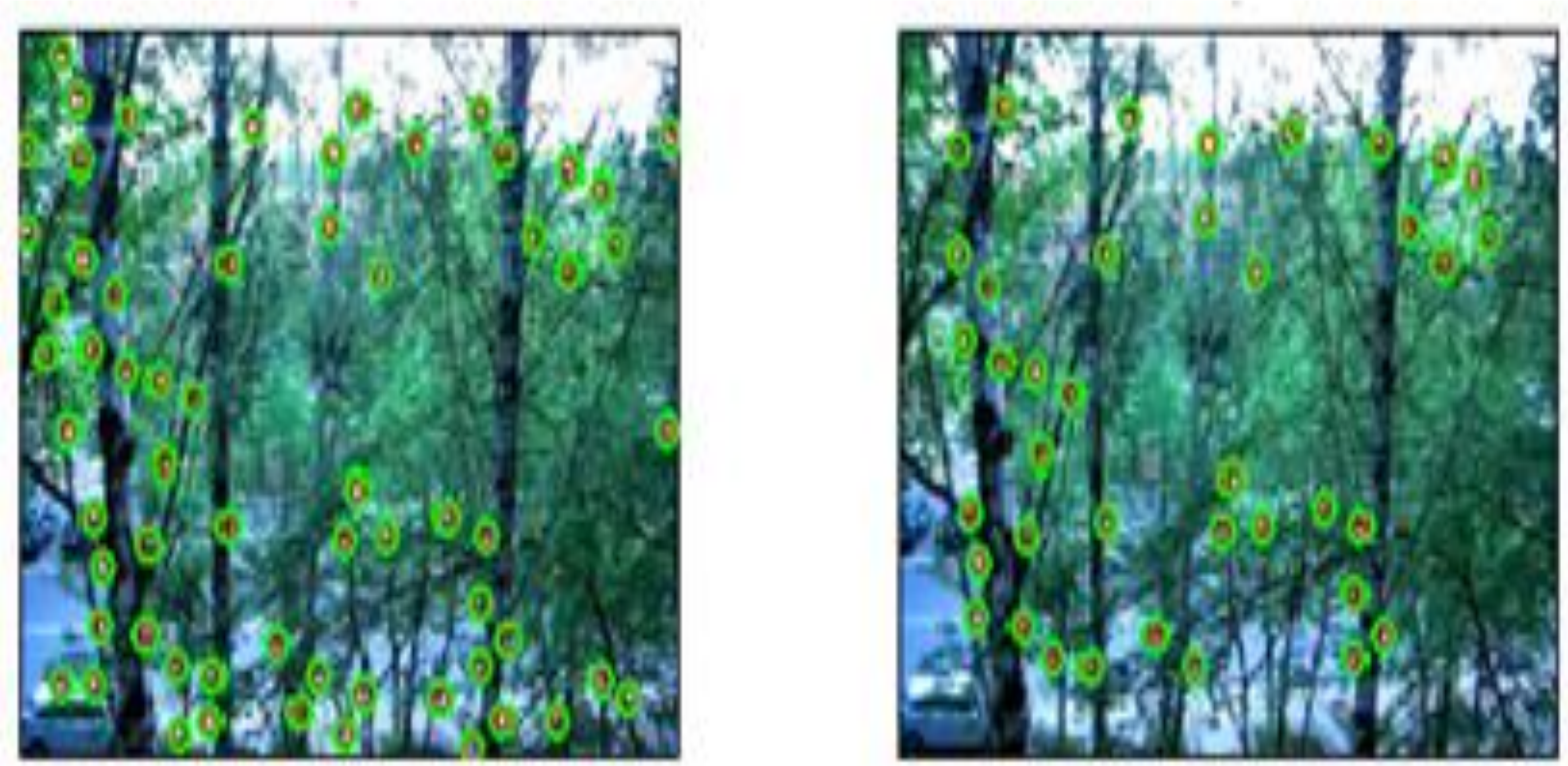
The first method

In **the first method**, we do not use any prior known maps or images of the area. There are **two sub-regimes**.

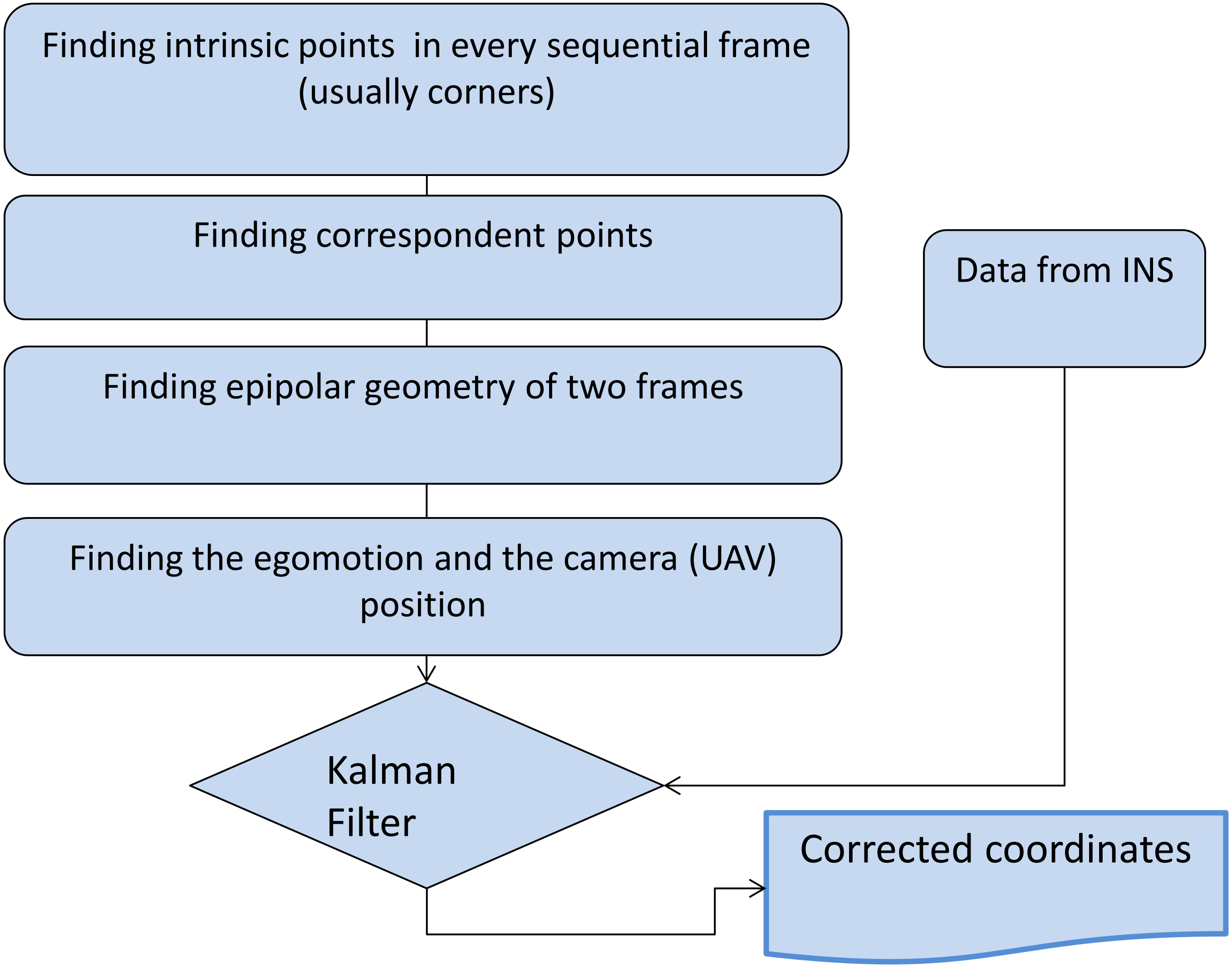
In **the first sub-regime**, the drone flies from an initial known point along a given route, using information only from a conventional primitive INS and camera. The calculation from the INS is corrected by measuring the relative displacement of “special” terrain points between vertical camera frames. This data is used for measuring the drone relative displacement each time. This sub-regime has an error that increases over time but is at the level of the best Inertial Navigation Systems (INS) for $100,000. In addition, you can use elements of Simultaneous Localization and Mapping (SLAM), i. e., in this flight we remember characteristic ground labels during the flight, which allow us to return absolutely exactly to the starting point of departure, if the target of the attack is not found. Such a problem cannot be solved only with the help of INS. Thus, using a conventional INS and a camera, we provide a fundamentally new quality - the return of the drone, and the navigation accuracy of the largest and most expensive INS.

In **the second sub-regime**, we use SLAM completely - we make repeated flights of the area around the starting point with returns and increasing distances, remember characteristic ground labels (or even produce complete maps of heights and images of the area); with each new return we know the position of the ground labels more accurately. This allows future flights to use these ground markers to accurately correct errors in determining the position and pose of the drone, i. e., eliminate increasing time errors during flying in the investigated area. In the second sub-mode, the navigation error will not increase over time due to the use of these corrections. In other words, this sub-mode allows you to create the necessary information about the terrain in the launch zone to prevent the calculation error from growing over time during repeated launches.

Correspondent intrinsic points



Metod1: finding coordinates' increments by the help of visual data flow



Finding intrinsic points in every sequential frame (usually corners)

Finding correspondent points

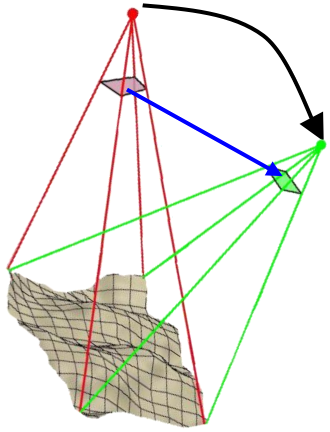
Finding epipolar geometry of two frames

Finding the egomotion and the camera (UAV) position

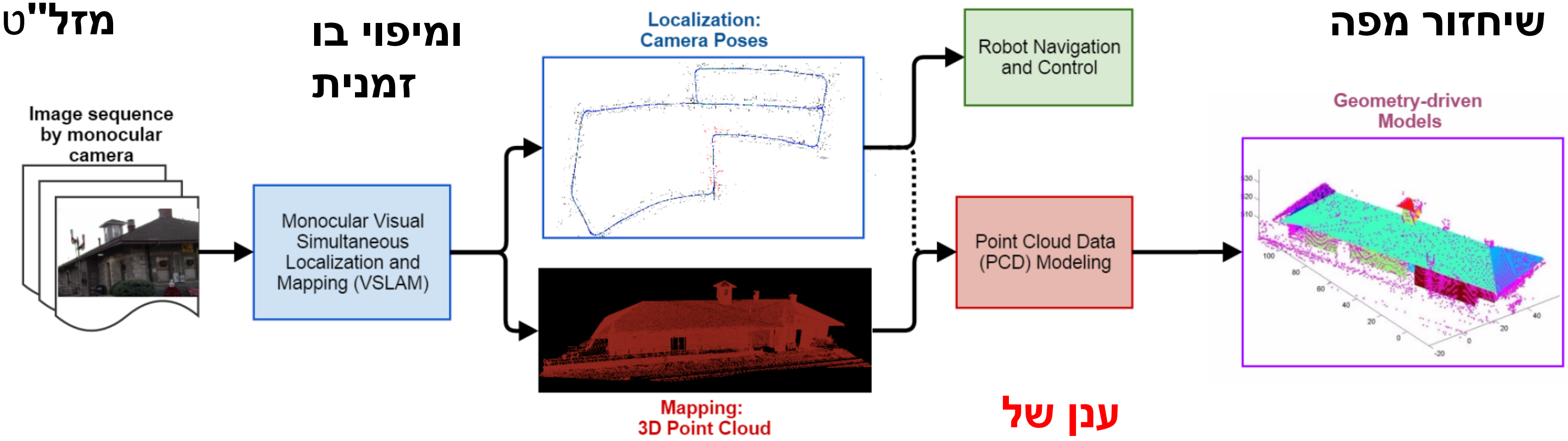
Data from INS

Kalman Filter

Corrected coordinates



לוקליזציה ומיפוי בו זמנית
Simultaneous localization and mapping (SLAM)



צילומים
ממצלמת
מזל"ט

לוקליזציה
ויזואלית
ומיפוי בו
זמנית

לוקליזציה
ויזואלית

מיפוי

ניווט ובקרה
של רובוט

ענן של
נקודות על
הקרקע

שיחזור מפה

The second navigation method

In **the second navigation method**, we use a priori known information about the relief elevation map on a given route, which must be entered into the computer’s memory before launching the drone. In this case, determining the location and pose of the drone is achieved by comparing the current terrain observed by the camera with the terrain on the input map. Since terrain is difficult to camouflage, this method is highly reliable. However, it is applicable only if there is rich terrain on the flight route (applicable only on very **NOT** flat terrain).

Method 2: : Finding position and orientation with the help of DTM.

Two consecutive images

Compute *n* feature correspondences

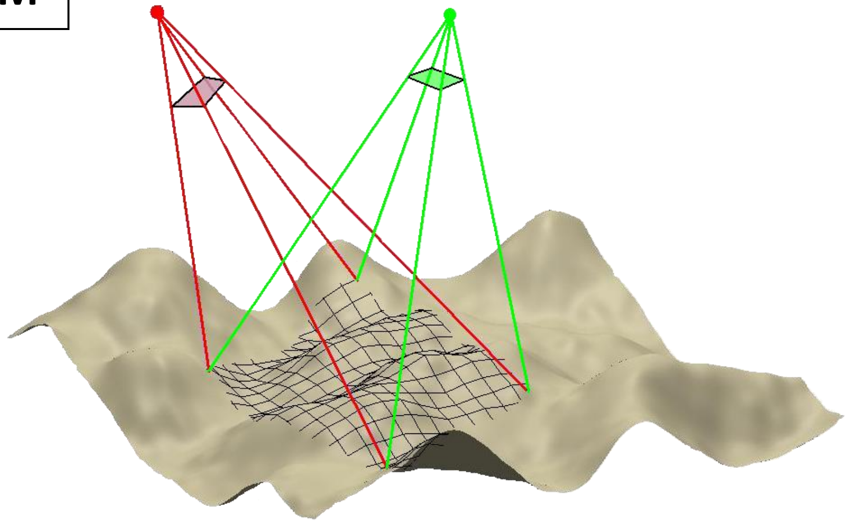
2n constraints (Δu, Δv)

Compute pose and ego-motion that best explain the features movement

DTM

Pose and ego-motion

12 variables



The third method

The third method uses additional information about a priori known images of the terrain, which must be entered into the computer’s memory before launching the drone. Navigation is carried out by comparing the current image from the camera with the image on the map. The method is very difficult to implement - the image of the terrain changes greatly when the position and pose of the drone changes, lighting, season, and changes in ground objects over time. With a single image, it is difficult to reconstruct the terrain. Very sophisticated identification algorithms are required that are robust to these changes. For these purposes, it is recommended to use modern artificial neural networks and advanced mathematical methods.

The third method

<u>תמונת מזל"ט</u>

<u>תמונת לווין</u>

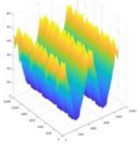
שיטה: השוואת נקודות עניין מקבילות

getOpticalFlowField2()

Actual camera image from UAV

Image of feature points from camera with actual position and orientation
detectSURFFeatures() , extractFeatures()

מפת גבהים של תא אחד

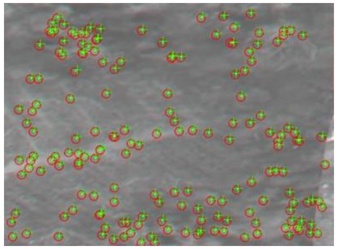


Orthophoto from cosmos(digital terrain map and brightness map)

Finding synthetic image for approximated position and orientation.
(**images_and_masks_generation2()**)
Finding feature points on synthetic image **detectSURFFeatures(), extractFeatures()**

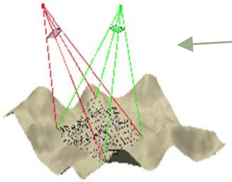
מפת בהירות של תא אחד

Finding shift of correspondent feature points
matchFeatures()



Finding correspondent points on orthophoto from cosmos(synthetic ground points) from correspondent feature points on synthetic image
intersect_qs_with_smoothDTM_ind()

Finding minimum of 6 variables(actual position and orientation) giving the best correspondence between synthetic ground points and correspondent feature points on actual camera image
estimateWorldCameraPose()

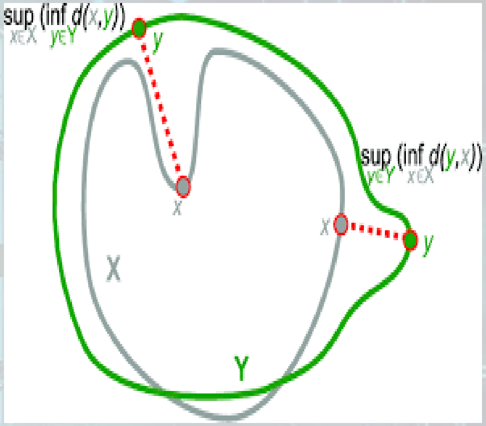


Actual position and orientation of camera and its errors from visual navigation

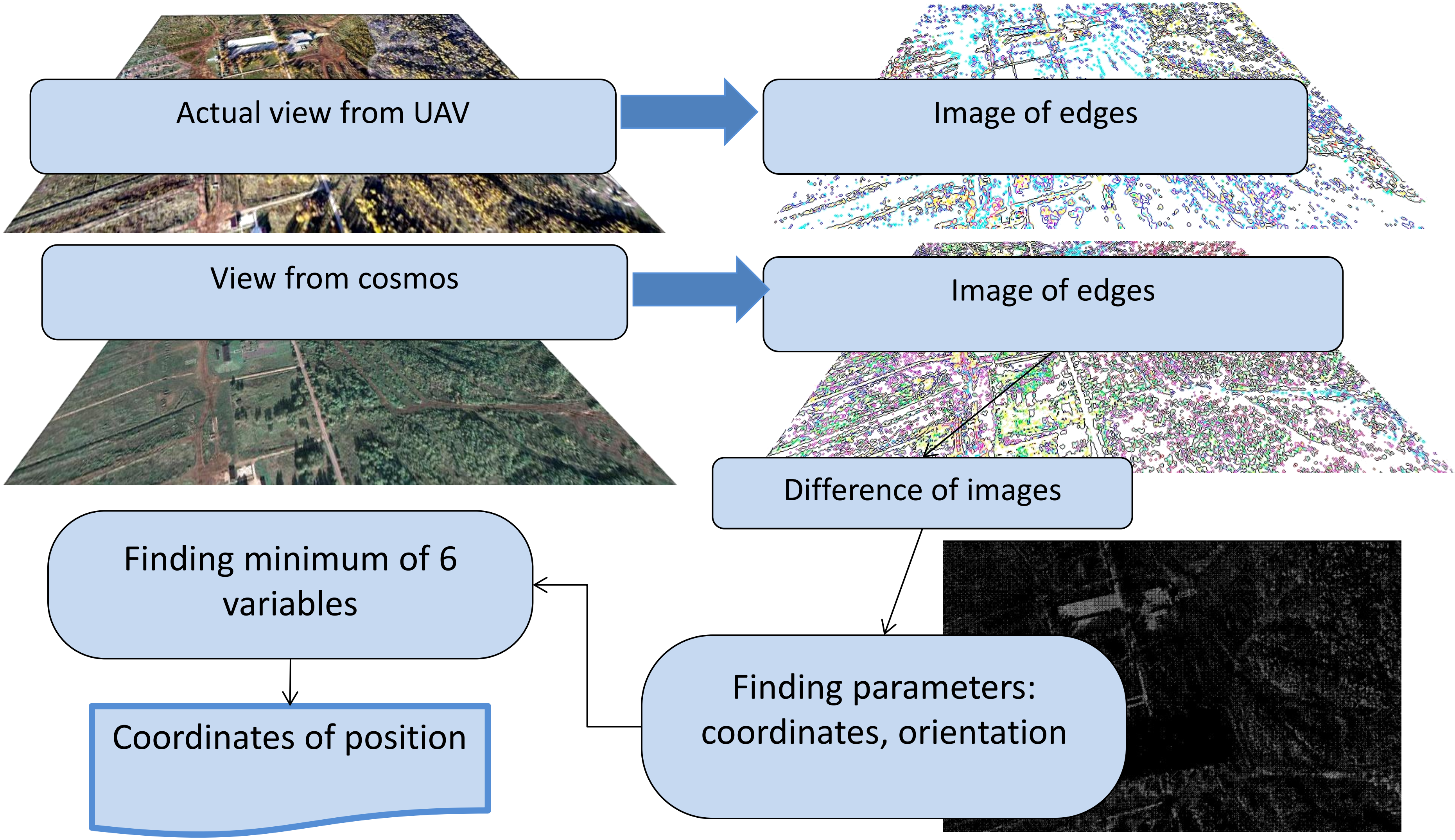
Direct algorithm - Hausdorff Distance

- The direct algorithm we built is based on the Hausdorff Distance tool which is used to calculate distances between points of interest in an image in order to analyze data and shapes in that image.

- We chose this algorithm because today it is widely used in image analysis, shape recognition and comparison between identical images. We believe it can be used to build an efficient algorithm for identifying identical objects in similar images.



Metod 3 : Finding position and orientation with the help of the archival photo using Hausdorff Distance



Actual view from UAV

Image of edges

View from cosmos

Image of edges

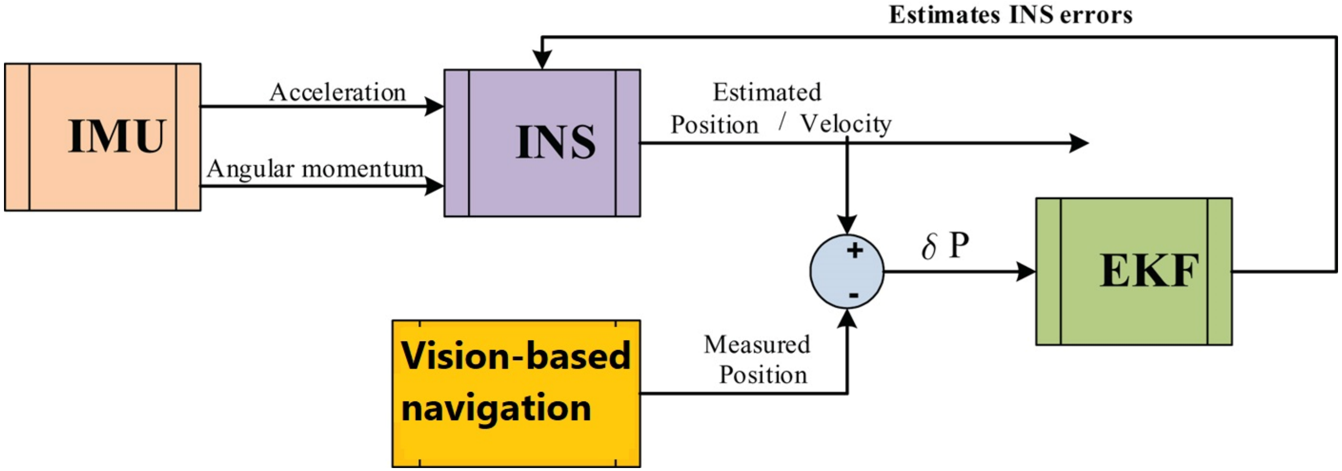
Difference of images

Finding parameters: coordinates, orientation

Finding minimum of 6 variables

Coordinates of position

מסנן קלמן לשילוב מערכת נווט מבוסס ראיה ממוחשבת עם מערכת אינרציאלית



Artificial Neural Network for recognition known 3D ground object

AlexNet

- AlexNet -

היא שיטה ליישום רשת נוירונים מלאכותית שפותחה על ידי אלכס קריזווסקי (Alex Krizhevsky).

- אלכס ושותפיו התחרו בשנת 2012 וזכו בכך ש
- AlexNet – היה האלגוריתם המהיר והיעיל ביותר בהבדל משמעותי.
- האלגוריתם מונה 25, במשך השנים האלגוריתם עבר לא מעט שיפורים וייעול.
- האלגוריתם גמיש מאוד וניתן להתאים אותו בדיוק רב ולכן בחרנו להשתמש בו.

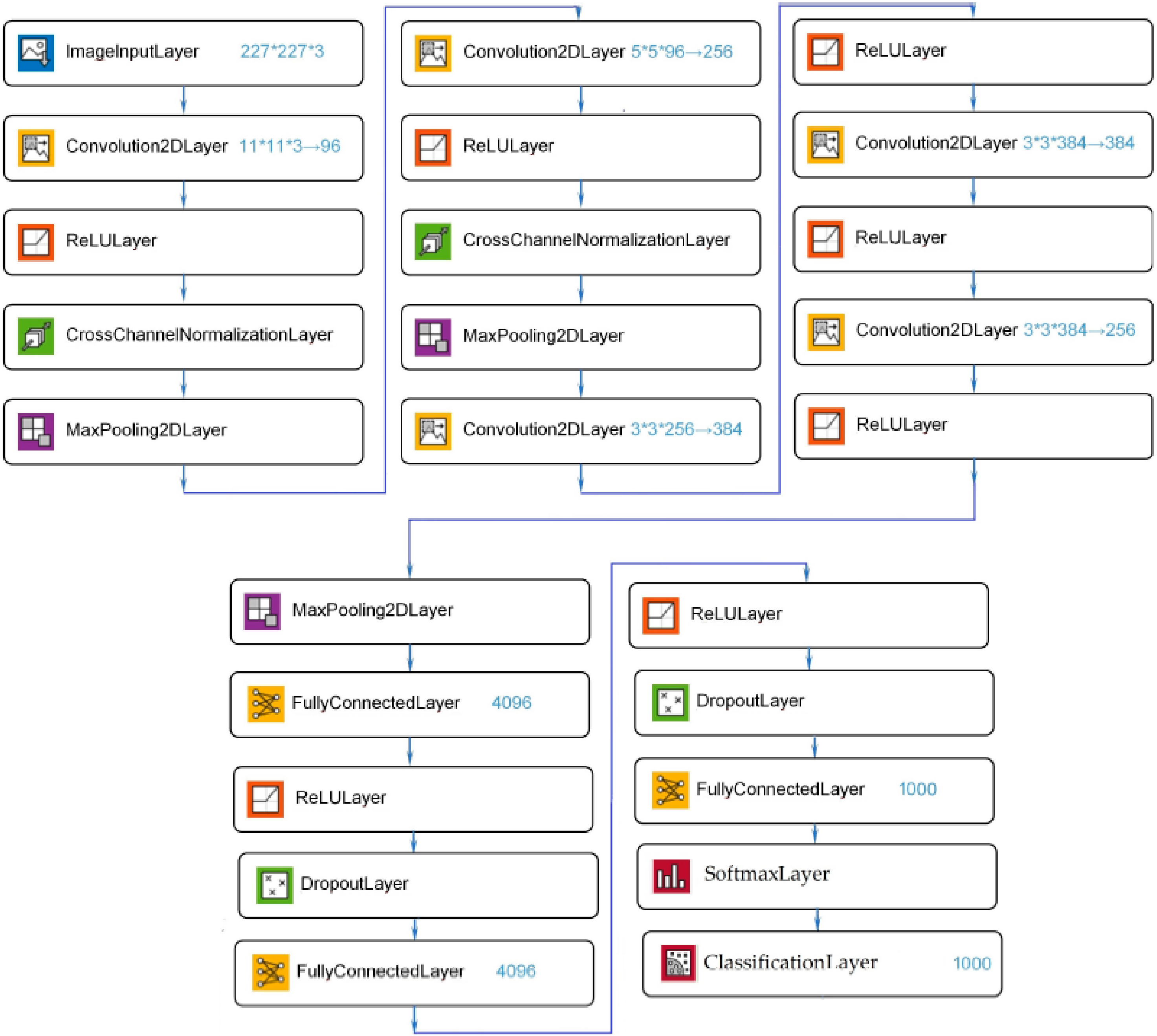


Figure 1. AlexNet in Matlab.

איסוף ועיבוד המידע

- לצורך המחקר אספנו 5000 תמונות של מבנה אקראי שמציגות את המבנה כמעט מכל וריאציה אפשרית.
- כל תמונה עוברת עיבוד וכיווץ והתאמה לדרישת האלגוריתם, התמונה מוקטנת ל227x227 פיקסלים ועוברת למערכת צבעים RGB.
- אספנו נתונים מדויקים של כל תמונה, פרמטרים עבור כל תמונה שמסבירה את המיקום המדויק של המצלמה במרחק ובזווית.

Artificial Neural Network for recognition drone photo on Satellite image and drone camera pose

Project goals:

Given a pair of images - a UAV image and a satellite image - our goal is to determine:

- **Identification and localization of the UAV image within the satellite image. In order to achieve this, we developed a neural network model whose first output is to identify and locate the UAV image within the satellite image.**

- **The UAV camera pose. The second output of the same neural network is to estimate the camera pose of the UAV.**

- **Synthetic UAV images for verification. By determining the location of the UAV image and camera pose within the satellite image, we can use homograph to produce a synthetic UAV image. We compare the synthetic image to the real image using a second Siamese network or Hausdorff Distance** method to validate the approach.

Continuation of the project goals:

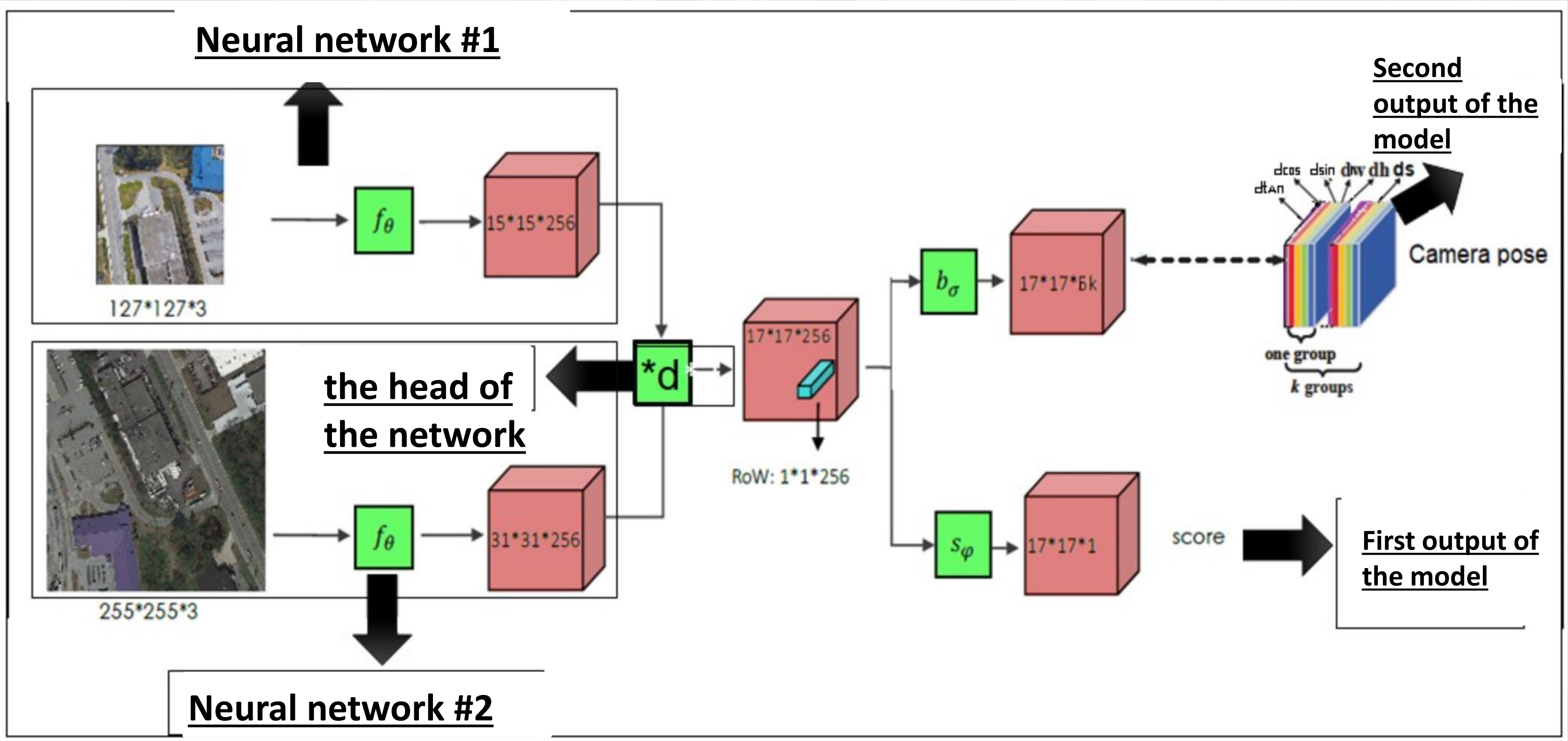
This project is based on previous projects in which the following goals were achieved:

- **We developed an initial Siamese neural network for identifying and locating UAV images within satellite imagery, as well as the UAV camera pose.** In this project, the network training process was not completed, so we will need to finish the training process and improve or even change the network according to the results.

- **We implemented a second Siamese neural network or Hausdorff Distance method to determine UAV camera pose and compare between similar images.** Also in this process, the network needs to be trained based on the output of the first network, and it will be modified according to the output results.

- **The overall goal is to develop and validate an integrative model that can determine UAV image location, camera pose, and achieve high accuracy.** The current project represents gradual progress towards this goal.

Our first model - Siamese neural network:



Neural network #1

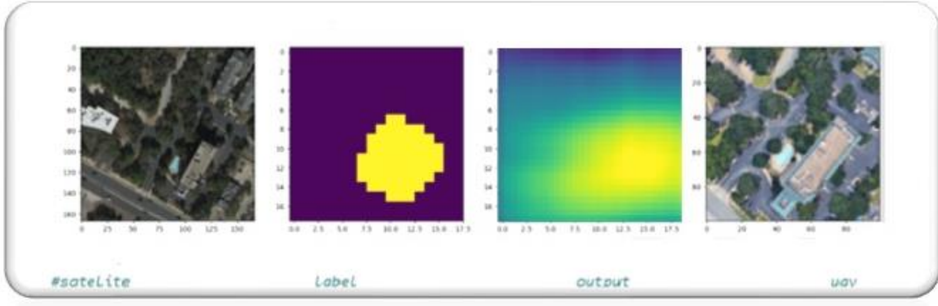
the head of the network

Neural network #2

Second output of the model

First output of the model

תוצאות



- כתבנו תוכנית שמייצגת רשת שציירנו קודם (שקף 3)
- עשינו ריצות על כמות קטנה של תמונות ב trainSet ו testSet
- ראינו שתוכנית רצה בלי שגיאות
- על התמונות ציירנו מקרים מוצלחים עבור ענף ראשון.

תמונה בצד שמאל היא תמונת לווין ,

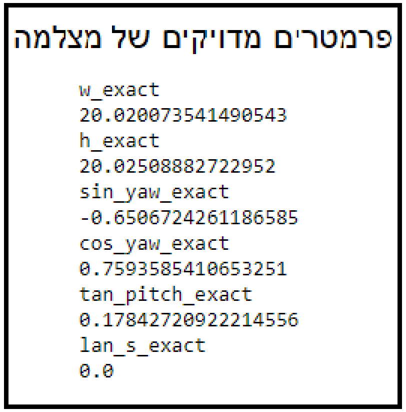
תמונה בצד ימין היא תמונת מזל"ט.

תמונות במרכז: תמונה מצד שמאל זה (רצוי) ומצד ימין פלט של הרשת (מצוי)**Label**

הרצנו את התוכנית על סט תמונות הרבה יותר גדול.

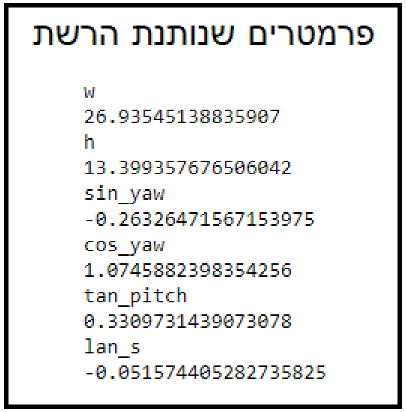
ומקבלים גם תוצאות של מיקום וכיוון של תמונת מזל"ט על תמונת לווין. אלה פרמטרים של מצלמת מזל"ט.

בצד שמאל רואים פרמטרים שנותנת הרשת ובצד ימין פרמטרים מדויקים של מצלמה.



פרמטרים מדויקים של מצלמה

```
w_exact
20.020073541490543
h_exact
20.02508882722952
sin_yaw_exact
-0.6506724261186585
cos_yaw_exact
0.7593585410653251
tan_pitch_exact
0.17842720922214556
lan_s_exact
0.0
```



פרמטרים שנותנת הרשת

```
w
26.93545138835907
h
13.399357676506042
sin_yaw
-0.26326471567153975
cos_yaw
1.0745882398354256
tan_pitch
0.3309731439073078
lan_s
-0.051574405282735825
```

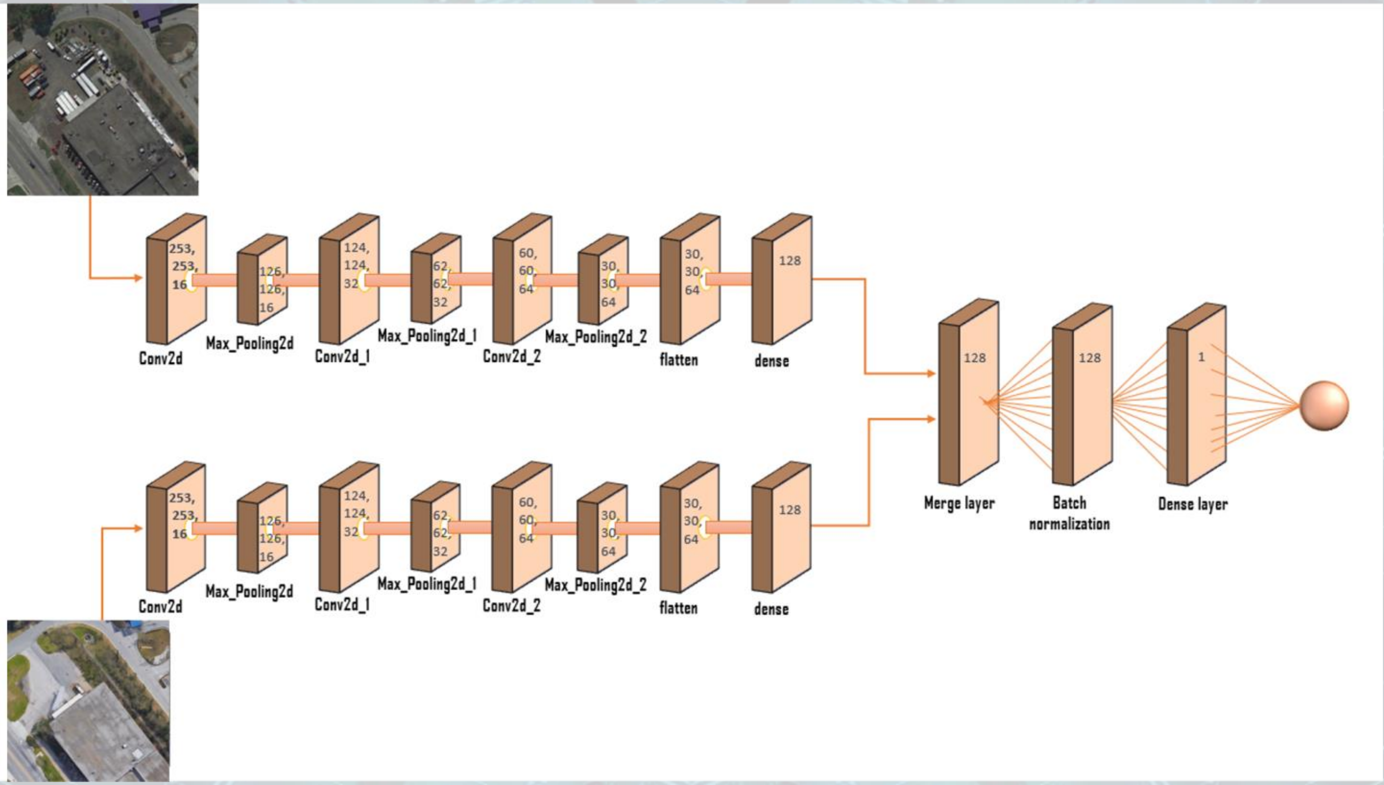
Synthetic drone image by homography

We have a UAV image (top left and also top right) and a satellite image (bottom left). After finding the location of the UAV image on the satellite image by applying a homograph transformation, we can find a synthetic UAV image (bottom right).

The two images on the right side will be used as input into a second Siamese neural network (or Hausdorff Distance method) for additional matching validation.

After this process, we will obtain a more successful matching accuracy.

Second Siamese Neural Network:



תוצאות-רשת נוירונים אל מול האלגוריתם המתמטי

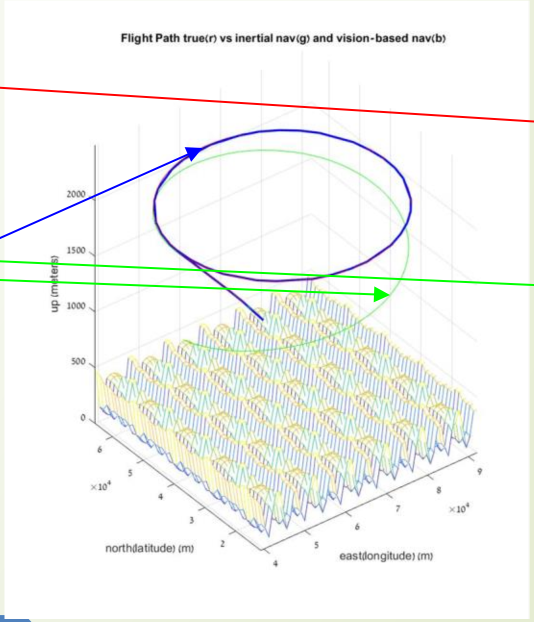
Hausdorff distance	רשת נוירונים סיאמית	
89.9%	90%	אחוזי הצלחה לאחר השוואה בין תמונות לוויין שונות המכילות אובייקטים זהים

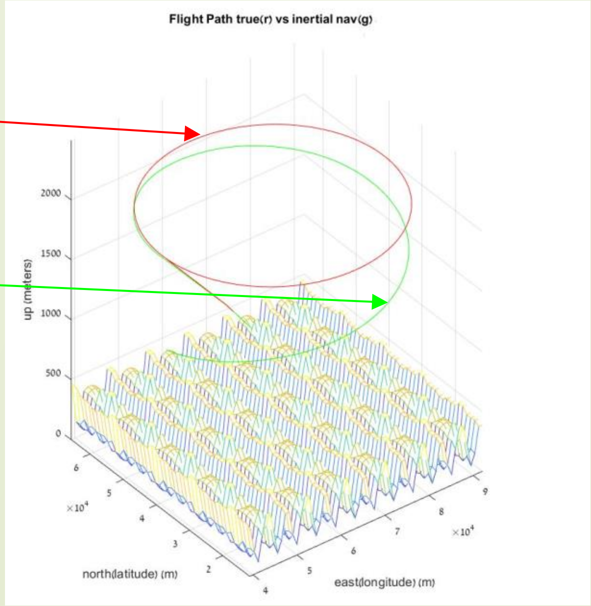
בהסתמך על התוצאות ובהשוואת שני המודלים אותם בנינו בפרויקט זה ניתן להסיק מספר מסקנות אותם ננתח בשקופית הבאה

מסלול מדויק בצבע אדום

שחזור מסלול בעזרת מערכת
אינרציאלית של 6צירים בצבע
ירוק

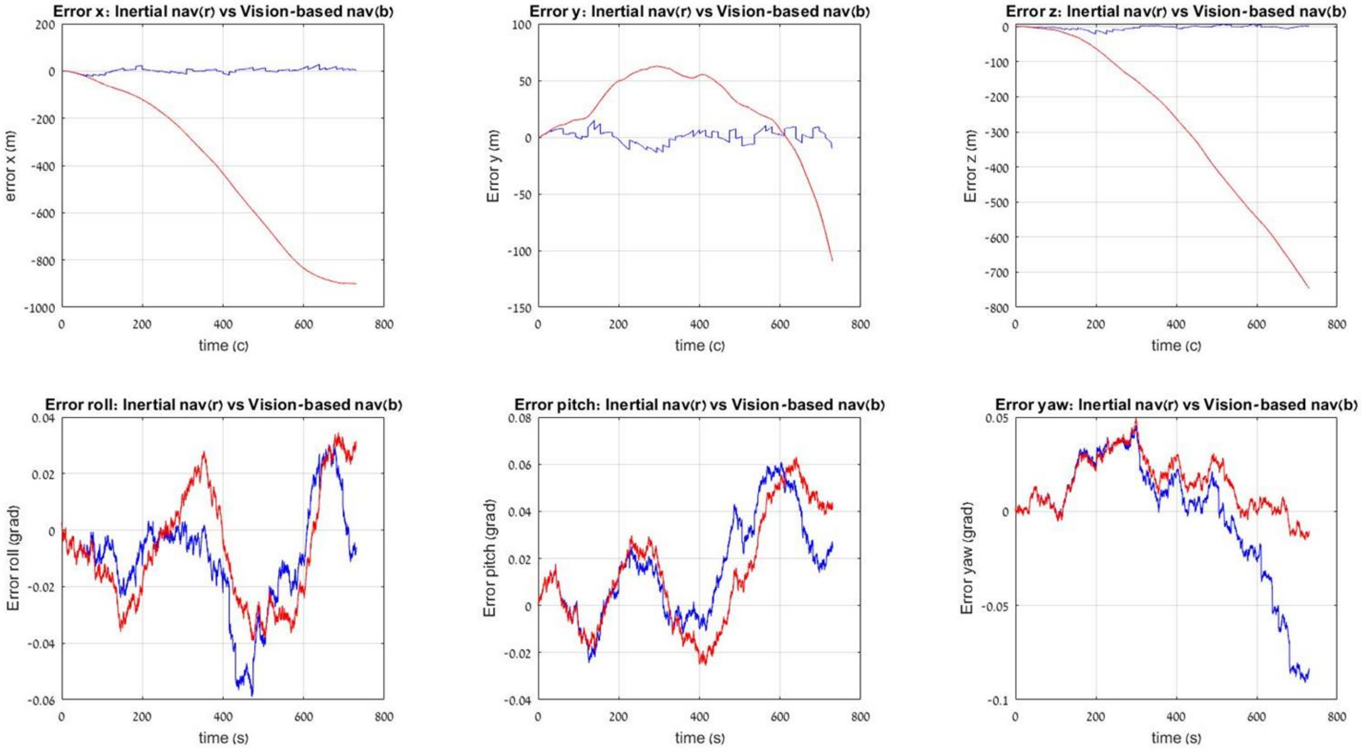
שחזור מסלול בעזרת שילוב
מערכת אינרציאלית ב 10צירים
וראייה ממוחשבת בעזרת מפת
גבהים ומפת בהירות בצבע
כחול





מתי עושים מדידה מבוססת ראייה ממוחשבת

- כאשר שגיאה נגררת של מערכת אינרציאלית מתחילה להיות גדולה יותר משגיאה של מערכת ראייה ממוחשבת .
- על התמונה רואים שגיאה של הפלט שלנו כיוון ומיקום של מצלמה.
- ורואים ששגיאה כבר לא גוררת ברגע ששגיאה במערכת אינרציאלית מספיק גדולה אנחנו מתקנים את זה ע"י מערכת ראייה ממוחשבת.

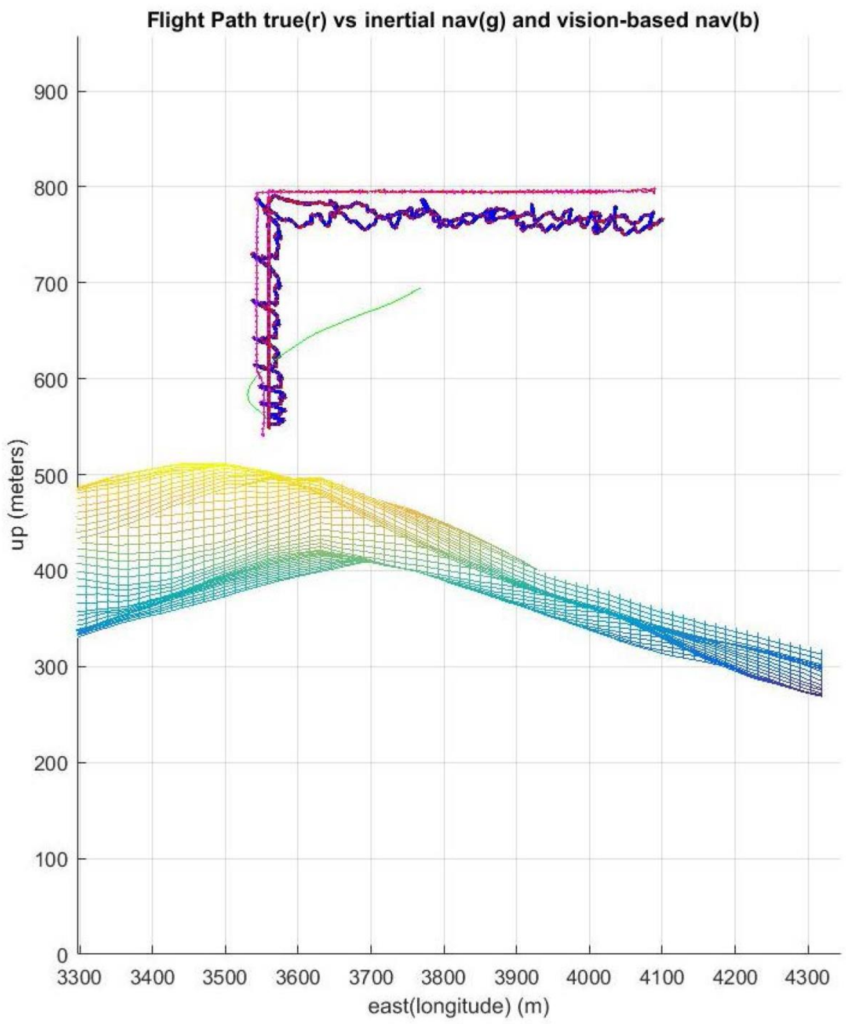


Real path 1

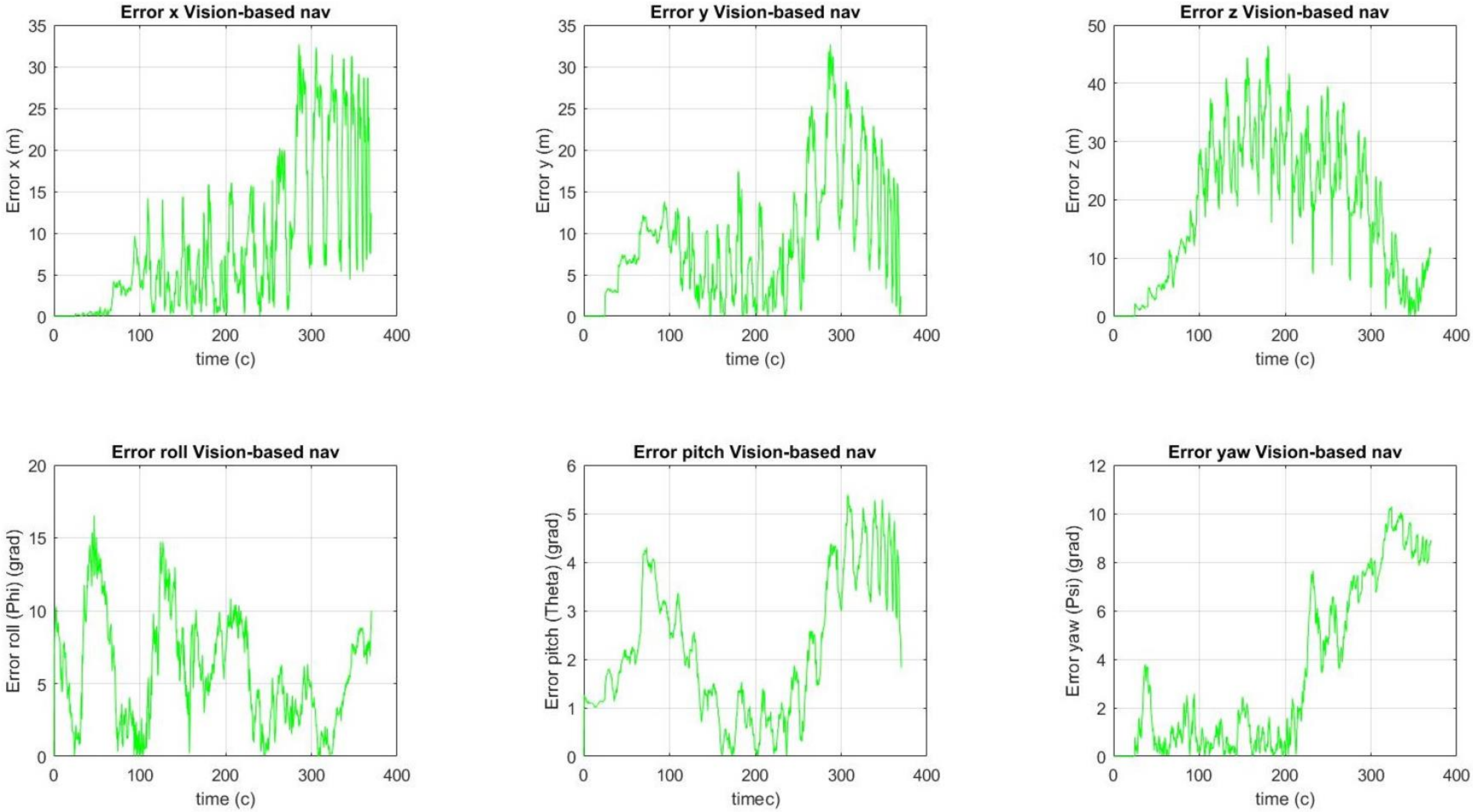
מסלול מדויק בצבע אדום

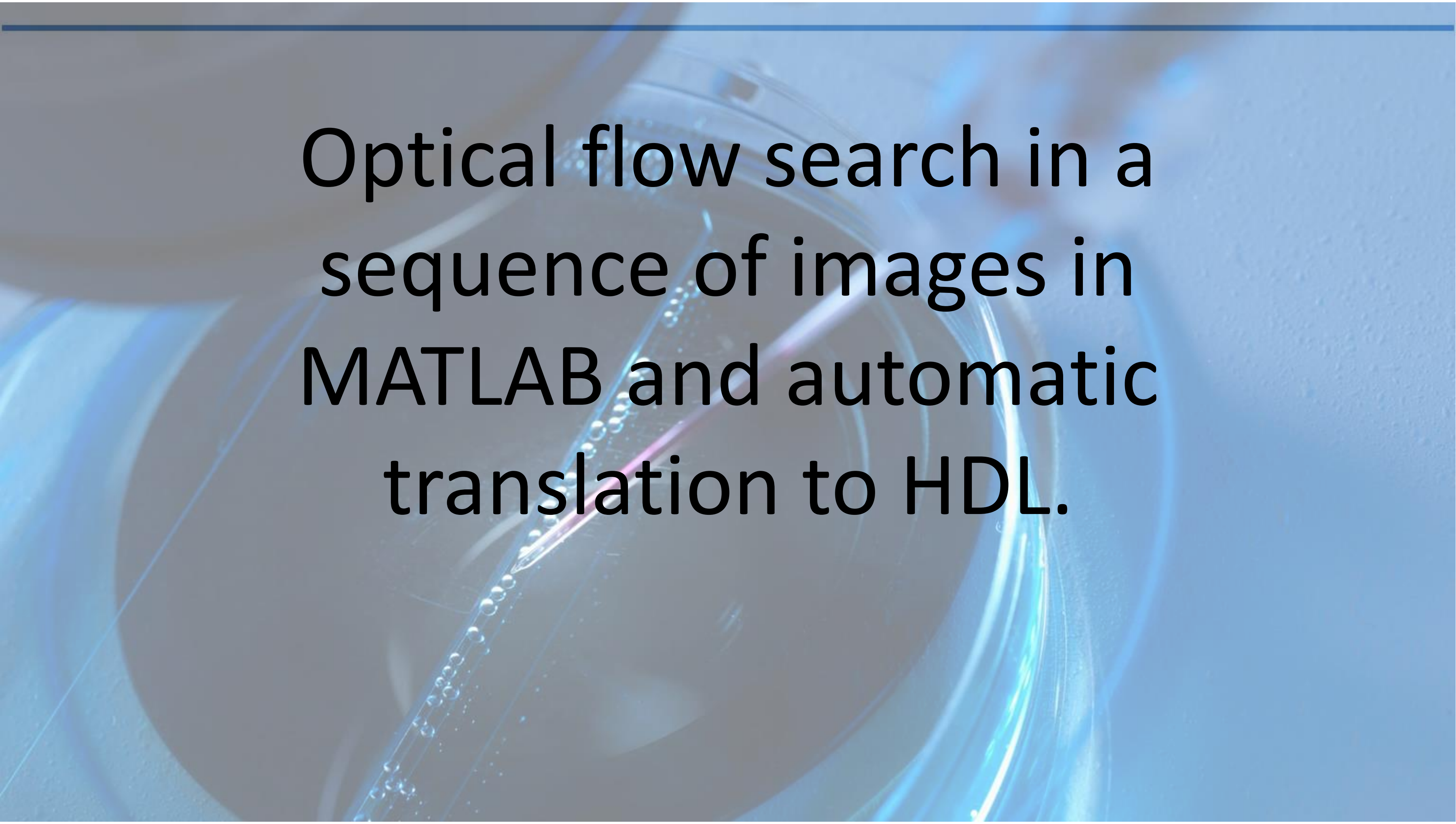
שחזור מסלול בעזרת מערכת אינרציאלית של 6צירים בצבע ירוק

שחזור מסלול בעזרת שילוב מערכת אינרציאלית ב 10צירים וראייה ממוחשבת בעזרת מפת גבהים ומפת בהירות בצבע כחול

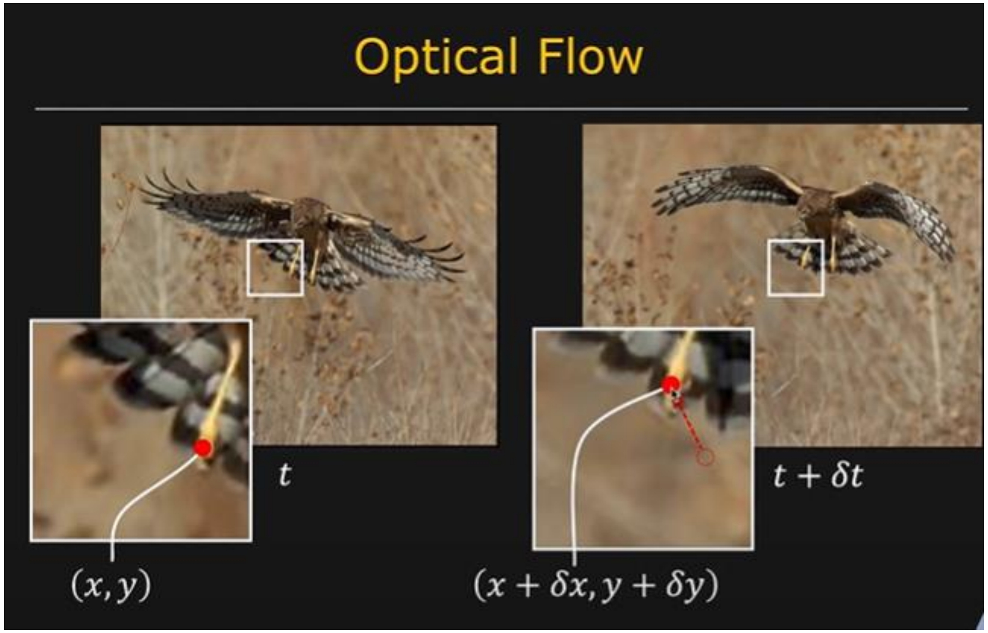


Real path 2


Error x Vision-based nav
Error x (m)
0
5
10
15
20
25
30
35
time (c)
0
100
200
300
400
Error y Vision-based nav
Error y (m)
0
5
10
15
20
25
30
35
time (c)
0
100
200
300
400
Error z Vision-based nav
Error z (m)
0
10
20
30
40
50
time (c)
0
100
200
300
400
Error roll Vision-based nav
Error roll (Phi) (grad)
0
5
10
15
20
time (c)
0
100
200
300
400
Error pitch Vision-based nav
Error pitch (Theta) (grad)
0
1
2
3
4
5
6
timec)
0
100
200
300
400
Error yaw Vision-based nav
Error yaw (Psi) (grad)
0
2
4
6
8
10
12
time (c)
0
100
200
300
400



Optical flow search in a sequence of images in MATLAB and automatic translation to HDL.

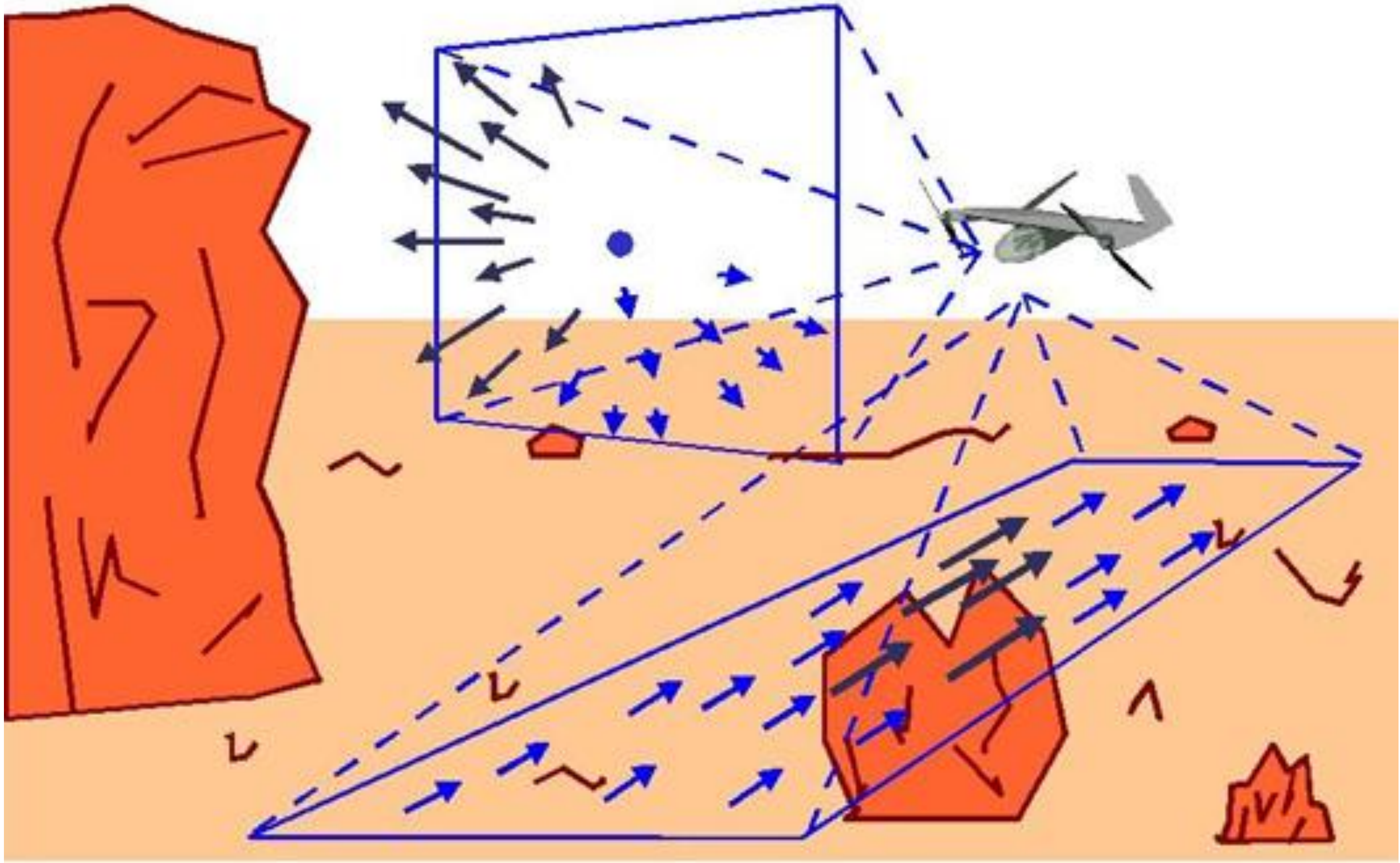


Introduction to Optical Flow

Optical flow is a computer vision technique used to track the motion of points in a sequence of images. In this project, we explore the implementation of optical flow algorithms in MATLAB and automatic translation of the program to hardware language HDl.

Optical flow for UAV camera
זרימה אופטית של מצלמת מזל''ט

מידע מצילומים
נוכחים



Lucas-Kanade method for optical flow calculation

$I(x,y,t) = I(x + \delta x, y + \delta y, t + \delta t)$

$$\frac{\partial I}{\partial x}\frac{\delta x}{\delta t} + \frac{\partial I}{\partial y}\frac{\delta y}{\delta t} + \frac{\partial I}{\partial t}\frac{\delta t}{\delta t} = 0$$

$$\frac{\partial I}{\partial x}V_x + \frac{\partial I}{\partial y}V_y + \frac{\partial I}{\partial t} = 0$$

$$\begin{aligned} I_x(q_1)V_x + I_y(q_1)V_y &= -I_t(q_1) \\ I_x(q_2)V_x + I_y(q_2)V_y &= -I_t(q_2) \\ &\vdots \\ I_x(q_n)V_x + I_y(q_n)V_y &= -I_t(q_n) \end{aligned}$$

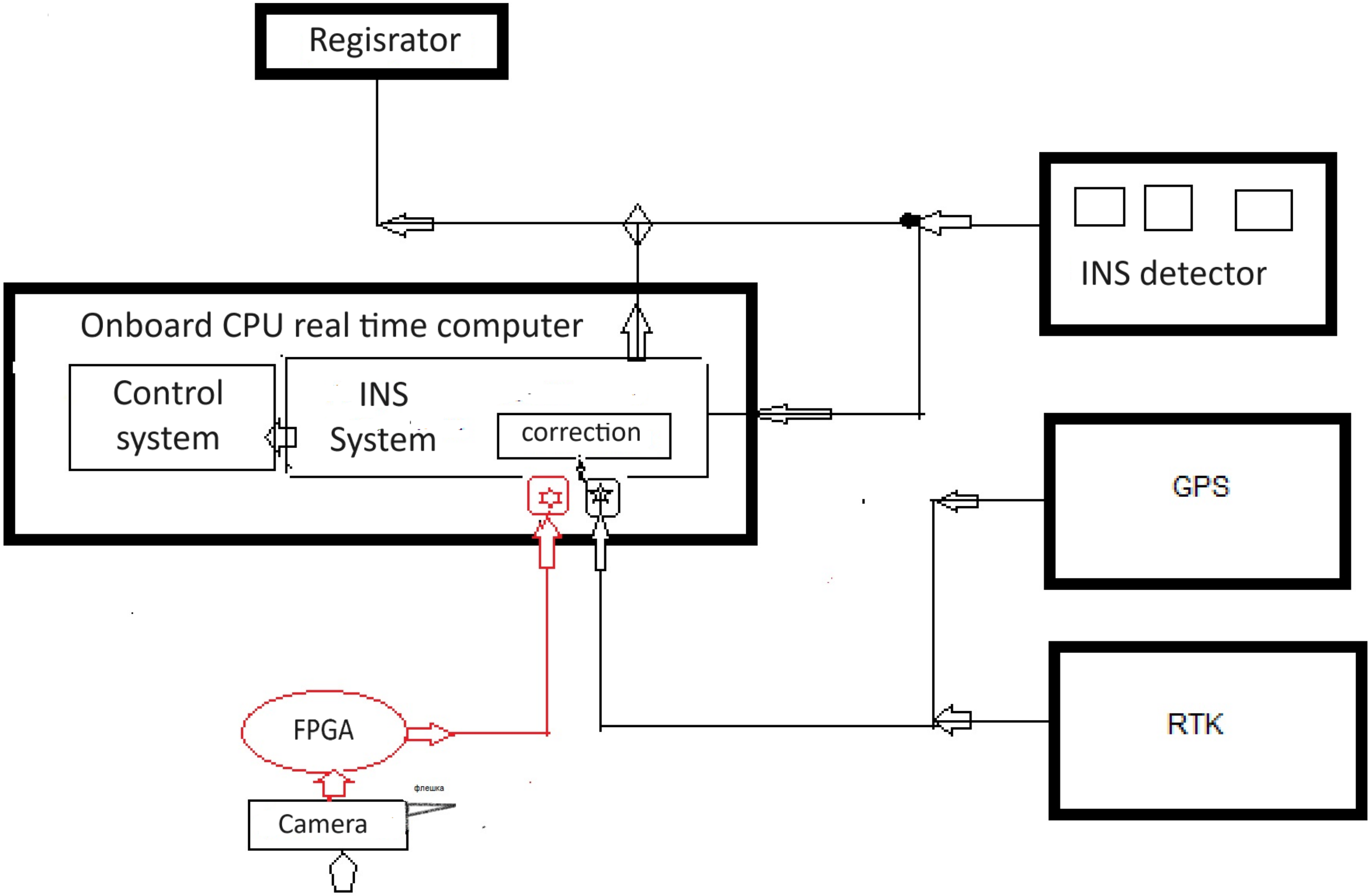
$$A = \begin{bmatrix} I_x(q_1) & I_y(q_1) \\ I_x(q_2) & I_y(q_2) \\ \vdots & \vdots \\ I_x(q_n) & I_y(q_n) \end{bmatrix}, \quad v = \begin{bmatrix} V_x \\ V_y \end{bmatrix}, \quad \text{and} \quad b = \begin{bmatrix} -I_t(q_1) \\ -I_t(q_2) \\ \vdots \\ -I_t(q_n) \end{bmatrix}$$

$A^T A v = A^T b$ or

$v = (A^T A)^{-1} A^T b$

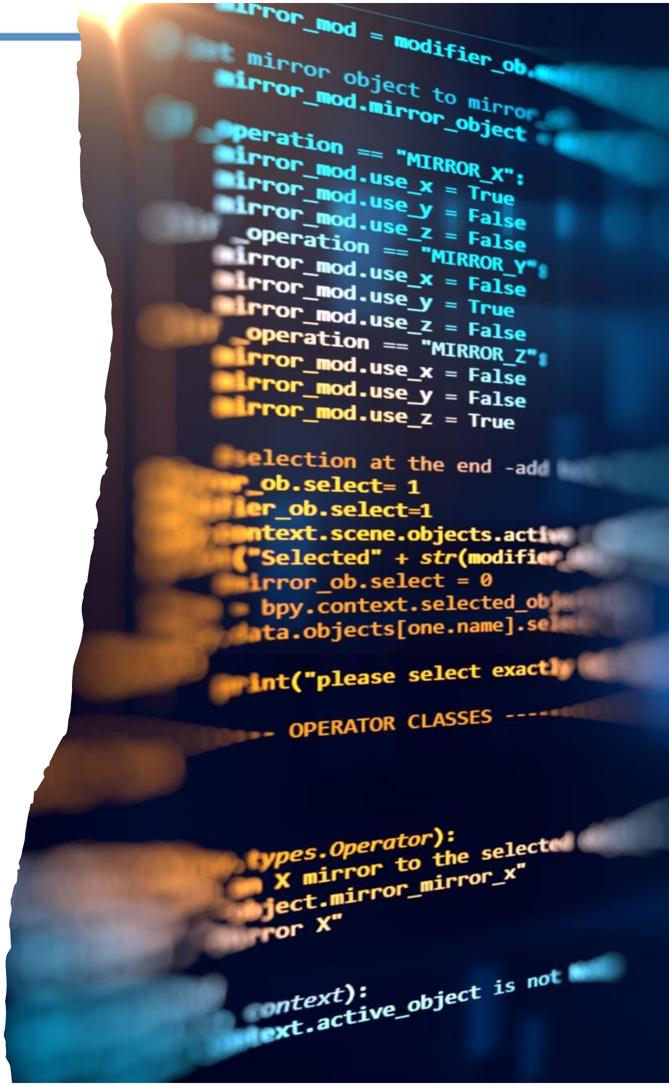
$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} \sum_i I_x(q_i)^2 & \sum_i I_x(q_i)I_y(q_i) \\ \sum_i I_x(q_i)I_y(q_i) & \sum_i I_y(q_i)^2 \end{bmatrix}^{-1} \begin{bmatrix} -\sum_i I_x(q_i)I_t(q_i) \\ -\sum_i I_y(q_i)I_t(q_i) \end{bmatrix}$$

Real time hardware



Tools and Methods for Implementation

- **MATLAB:** Utilizing MATLAB for its advanced image processing capabilities, offering a flexible environment for algorithm development and testing.
- **HDL CODER:** Toolbox in Matlab for automatic translation from Matlab to HDL
- **Hardware Description Language (HDL) Tools:** Employing HDL tools to translate MATLAB processes into hardware, ensuring a smooth integration of software-based algorithms with low-level hardware programming.
- **Efficiency Enhancement:** The integrated toolset enhances efficiency and effectiveness, ensuring the successful execution of the project's objectives.

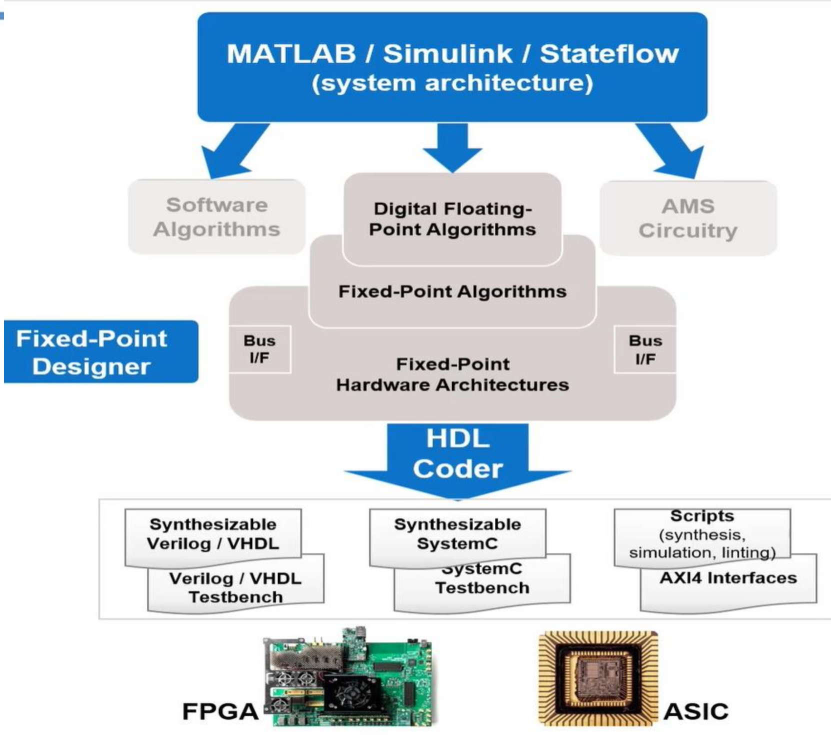


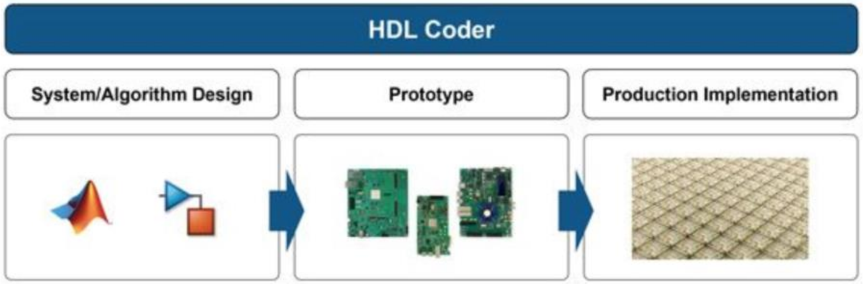
The process of creating a program in the project.

At the beginning, we write a program in MATLAB and then convert it to FIXED POINT form. This initial program is slow, utilizing expensive hardware with significant power requirements and large weight.

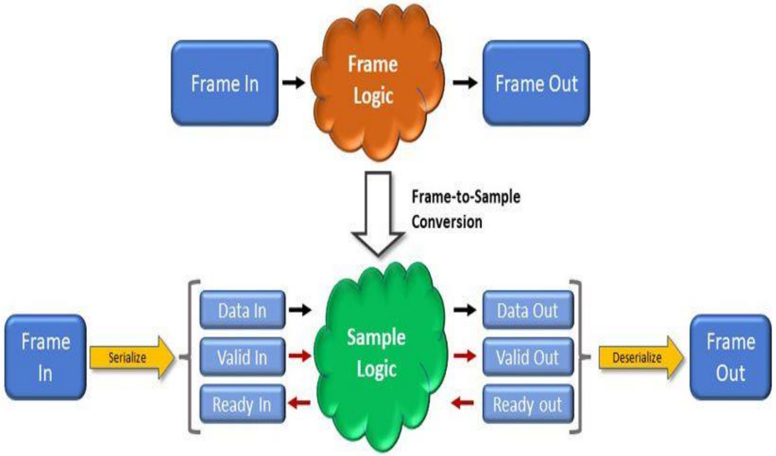
Subsequently, we employ CODER HDL to translate the program into HDL language for FPGA hardware. This hardware operates in real-time; however, it remains expensive, uses considerable amount of power, has large weight. These issues appear because of possibility to change its program. However, once we have a finalized program that works, there is no need to form its further modifications.

At this point, we can make transition from FPGA to ASIC. In ASIC, modifications of its program are not possible; the software is written once. ASIC is significantly cheaper, consumes much less power, has much smaller weight. It allow us to produce the hardware in large quantities for the low-cost production (mass production).





Challenges of automatic translation from MATLAB to HDL.

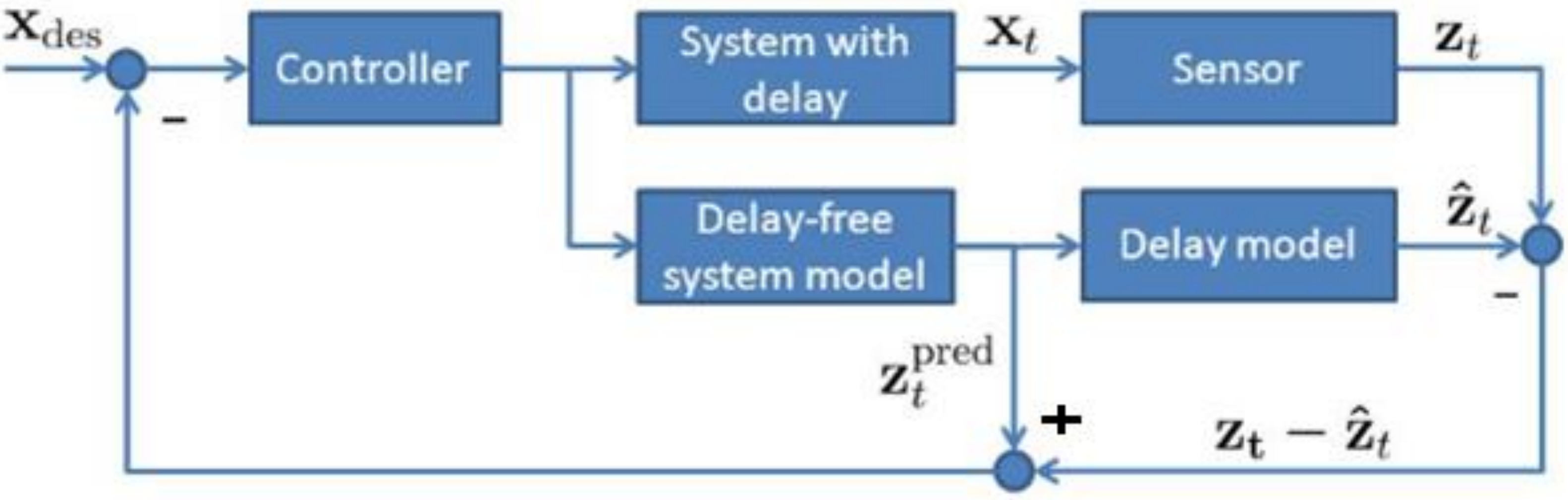


- The main goal of the project: We already have a working program for optical flow, but we need to modify it to a robust algorithm for which it is possible to perform automatic translation.
- Indeed, It is not possible to automatically translate any MATLAB program that we want.
- For example, we need to preprocess the program input so that the hardware receives not the entire image immediately, but only sequence of its portions. This is because the hardware input has a limited size. The transition from input that includes the entire image to input that includes only sequence of its portions is drawn on the left side of the slide.
- The second example of translation issues : some MATLAB functions cannot be translated into HDL.
- The third example of translation issues: many operations with matrices is necessary to replace to loops.
- There are also many other issues, so such translation is a complex task. We need to consider all the constraints, to modify existing algorithm correspondingly and to get a robust algorithm for which it is possible to perform automatic translation.

THE NEED (2)

Time delay of vision-based navigation

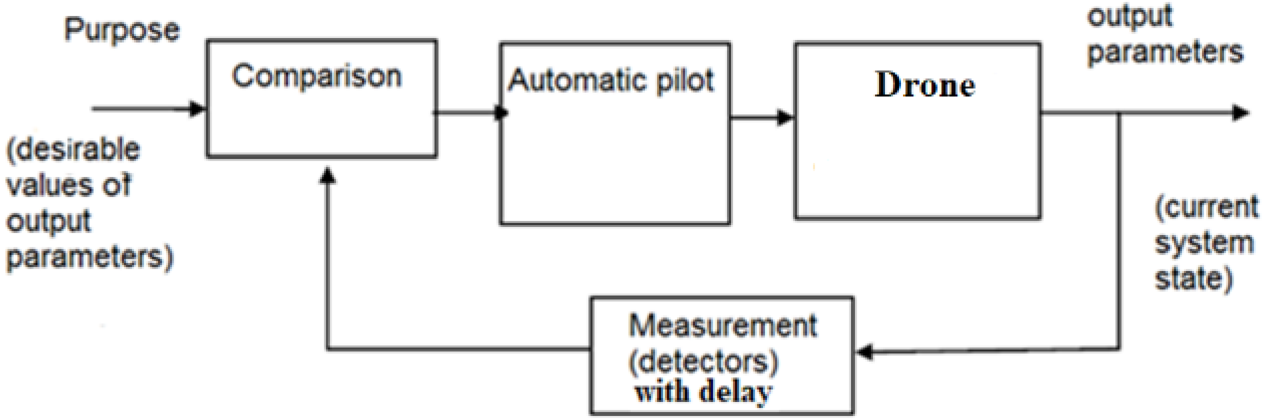
Unfortunately, there always exists noticeable delay in getting information about the output-controlled parameters to autopilot for vision-based navigation measurements. So, we have a problem, because of the lack of some necessary information for controlling.



Solution (the need 2)

Ravi P. Agarwal, Leonid Berezansky, Elena Braverman, Alexander Domoshnitsky, NONOSCILLATION THEORY OF FUNCTIONAL DIFFERENTIAL EQUATIONS WITH APPLICATIONS, **Springer, New York** 2012

Automatic control



Purpose

(desirable values of output parameters)

Comparison

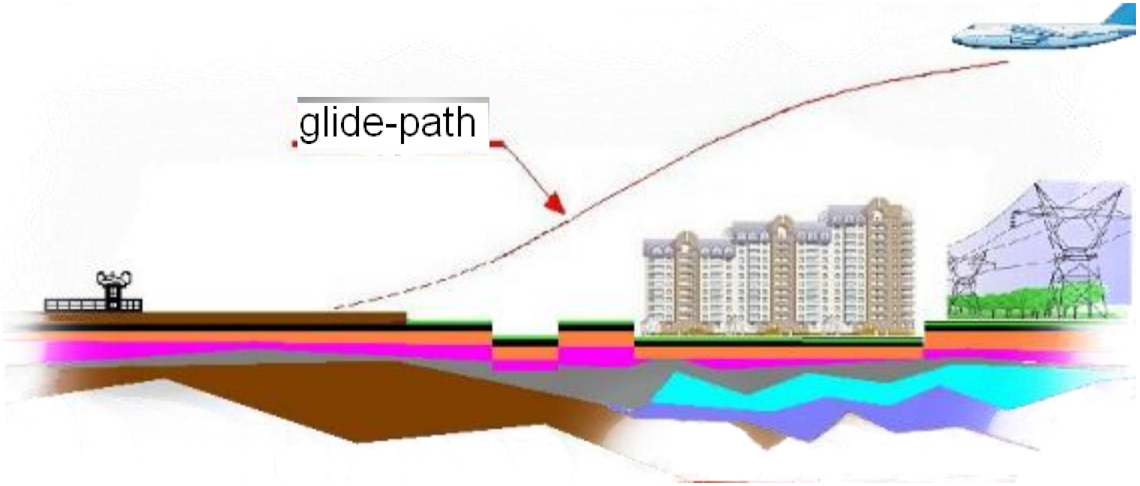
Automatic pilot

Drone

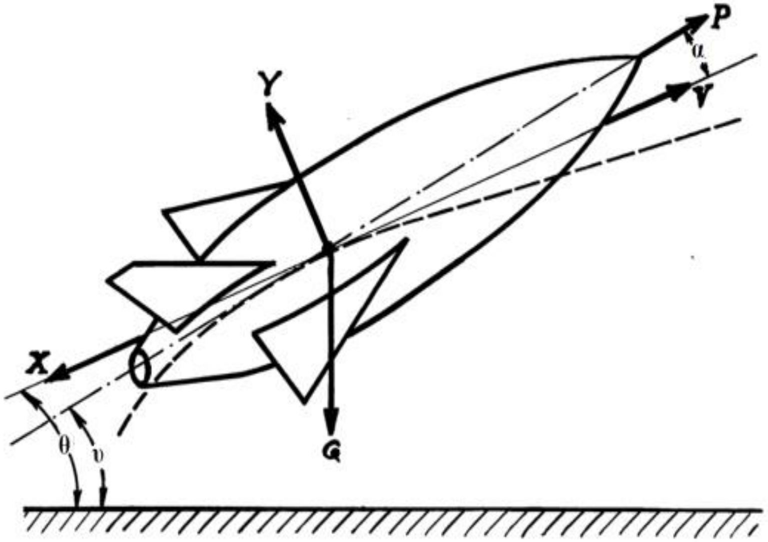
output parameters

(current system state)

Measurement (detectors) **with delay**



Parameters of drone’s motion



V - flight velosity tangent to trajectory
Y - carrying force ortogonal to flight velosity
X - resistance force opposite to V
G - gravitational force
υ - pitch angle, i.e. angle between lengthwise drone axis and horizontal plane
θ - tilting of trajectory about horizontal plane
α - angle of attack, i.e. angle between lengthwise axis and projection of velosity on the symmertry plane of drone
m = G/g - drone mass
P - tractive force directed along lengthwise dron axis

$$m\frac{dV}{dt} = P\cos\alpha - X - G\sin\theta$$

$$mV\frac{d\theta}{dt} = P\sin\alpha + Y - G\cos\theta$$

$$J_z\frac{d^2\nu}{dt^2} = M_z$$

$$\frac{dH}{dt} = V\sin\theta + U_y$$

$$\frac{dL}{dt} = V\cos\theta + U_x$$

$$P = P(\delta_p, V) \qquad \nu = \theta + \alpha$$

$$X = c_x S\frac{\rho V^2}{2} \qquad Y = c_y S\frac{\rho V^2}{2}$$

$$c_x = c_x(\alpha, \nu, V, H);$$

$$c_y = c_y(\alpha, V, H);$$

$$M_z = m_z b_a S\frac{\rho V^2}{2}$$

$$m_z = m_z(\alpha, \dot{\alpha}, \dot{\nu}, V, \delta_B, \rho)$$

δ_p - position of control knob

δ_B - deviation of elevator

Nonlinear equations of motion

$$m\frac{dV}{dt} = P\cos\alpha - X - G\sin\theta$$

$$mV\frac{d\theta}{dt} = P\sin\alpha + Y - G\cos\theta$$

$$J_z\frac{d^2\nu}{dt^2} = M_z$$

$$\frac{dH}{dt} = V\sin\theta + U_y$$

$$\frac{dL}{dt} = V\cos\theta + U_x$$

$$\mathrm{P} = \mathrm{P}(\delta_p, V)$$

$$\nu = \theta + \alpha$$

$$X = c_x S\frac{\rho V^2}{2} \qquad Y = c_y S\frac{\rho V^2}{2}$$

$$c_x = c_x(\alpha, \nu, V, H);$$

$$c_y = c_y(\alpha, V, H);$$

$$M_z = m_z b_a S\frac{\rho V^2}{2}$$

$$m_z = m_z(\alpha, \dot{\alpha}, \dot{\nu}, V, \delta_B, \rho)$$

Mz - total moment of aerodynamical forces with respect to transversal axis z

Jz - inertial moment of drone with respect of axis z

ρ - air density

Ux and Uy - wind velosities with respect axes x and y, correspondently

S - area of winds

b_a – length of wind chord

m_z - coefficient of moment

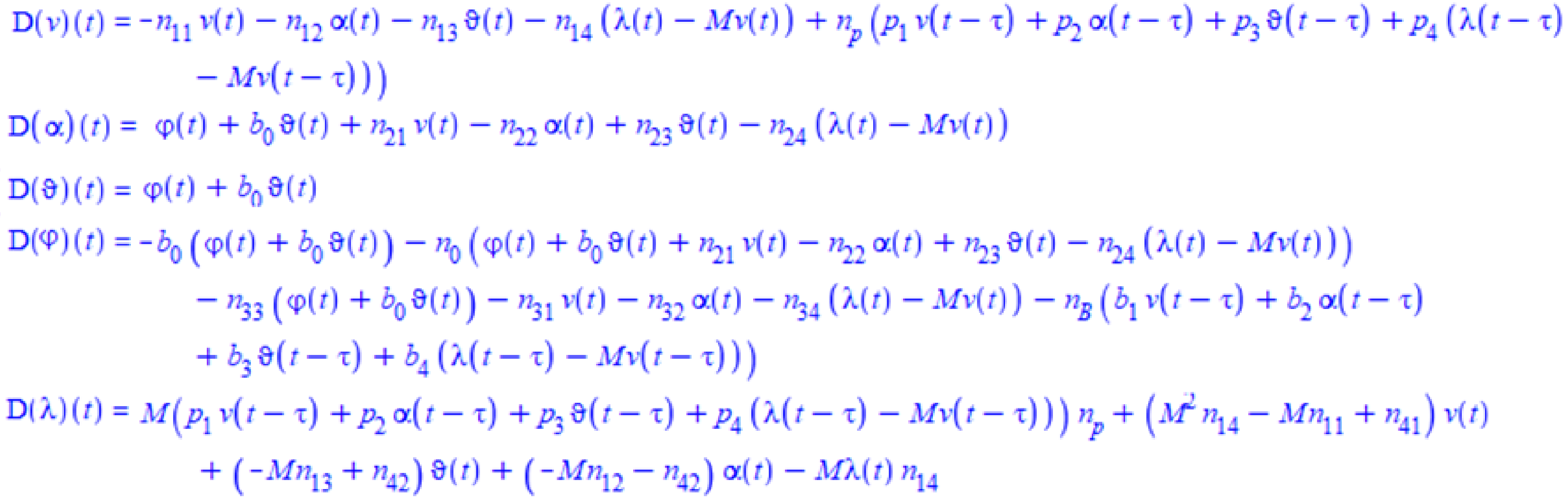
c_x and c_y - coefficients of resistance and carrying forces, correspondently

δ_p - position of control knob

δ_B - deviation of elevator

Linear equations of motion

משוואות דיפרנציאליות מסדר ראשון לתנועה אנכית עם זמן:



$$\begin{aligned}
\mathrm{D}(v)(t) = {} & -n_{11}\,v(t) - n_{12}\,\alpha(t) - n_{13}\,\vartheta(t) - n_{14}\left(\lambda(t) - Mv(t)\right) + n_p\left(p_1\,v(t-\tau) + p_2\,\alpha(t-\tau) + p_3\,\vartheta(t-\tau) + p_4\left(\lambda(t-\tau)\right.\right. \\
& \left.\left. - Mv(t-\tau)\right)\right)
\end{aligned}$$

$$\mathrm{D}(\alpha)(t) = \varphi(t) + b_0\,\vartheta(t) + n_{21}\,v(t) - n_{22}\,\alpha(t) + n_{23}\,\vartheta(t) - n_{24}\left(\lambda(t) - Mv(t)\right)$$

$$\mathrm{D}(\vartheta)(t) = \varphi(t) + b_0\,\vartheta(t)$$

$$\begin{aligned}
\mathrm{D}(\varphi)(t) = {} & -b_0\left(\varphi(t) + b_0\,\vartheta(t)\right) - n_0\left(\varphi(t) + b_0\,\vartheta(t) + n_{21}\,v(t) - n_{22}\,\alpha(t) + n_{23}\,\vartheta(t) - n_{24}\left(\lambda(t) - Mv(t)\right)\right) \\
& - n_{33}\left(\varphi(t) + b_0\,\vartheta(t)\right) - n_{31}\,v(t) - n_{32}\,\alpha(t) - n_{34}\left(\lambda(t) - Mv(t)\right) - n_B\left(b_1\,v(t-\tau) + b_2\,\alpha(t-\tau)\right. \\
& \left. + b_3\,\vartheta(t-\tau) + b_4\left(\lambda(t-\tau) - Mv(t-\tau)\right)\right)
\end{aligned}$$

$$\begin{aligned}
\mathrm{D}(\lambda)(t) = {} & M\left(p_1\,v(t-\tau) + p_2\,\alpha(t-\tau) + p_3\,\vartheta(t-\tau) + p_4\left(\lambda(t-\tau) - Mv(t-\tau)\right)\right) n_p + \left(M^2\,n_{14} - Mn_{11} + n_{41}\right) v(t) \\
& + \left(-Mn_{13} + n_{42}\right)\vartheta(t) + \left(-Mn_{12} - n_{42}\right)\alpha(t) - M\lambda(t)\,n_{14}
\end{aligned}$$

Stability of the system.

Theorem

We study stability of the following system:

$$x_i'(t) + \sum_{j=1}\sum_{k=1} a_{ij}^k(t)x_j(t - \theta_{ij}^k(t)) = 0, \quad t \in [0, +\infty),$$

$$i = 1, \dots, n,$$

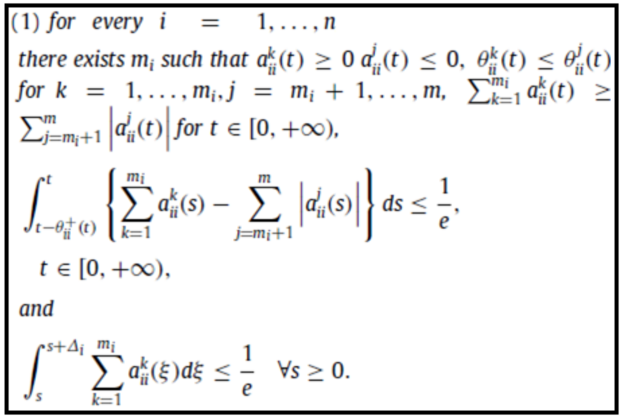
$$x_i(\xi) = 0, \quad \xi < 0,\ i = 1, \dots, n,$$

where $a_{ij}^k \in L_\infty$, $\theta_{ij}^k \in L_\infty$ for $k = 1, \dots, m$.

Stability of the system.

Theorem

Theorem. If the following conditions are fulfilled, then the system is exponentially stable.



(1) *for every* $i = 1, \dots, n$

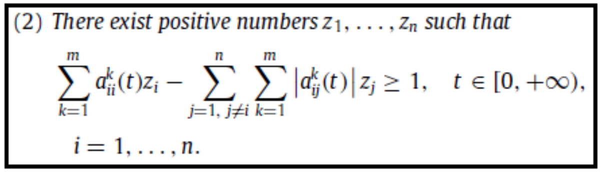
there exists m_i *such that* $a_{ii}^k(t) \geq 0$ $a_{ii}^j(t) \leq 0$, $\theta_{ii}^k(t) \leq \theta_{ii}^j(t)$ *for* $k = 1, \dots, m_i, j = m_i + 1, \dots, m$, $\sum_{k=1}^{m_i} a_{ii}^k(t) \geq \sum_{j=m_i+1}^{m} \left| a_{ii}^j(t) \right|$ *for* $t \in [0, +\infty)$,

$$\int_{t-\theta_{ii}^{+}(t)}^{t} \left\{ \sum_{k=1}^{m_i} a_{ii}^k(s) - \sum_{j=m_i+1}^{m} \left| a_{ii}^j(s) \right| \right\} ds \leq \frac{1}{e},$$

$t \in [0, +\infty)$,

and

$$\int_{s}^{s+\Delta_i} \sum_{k=1}^{m_i} a_{ii}^k(\xi) d\xi \leq \frac{1}{e} \quad \forall s \geq 0.$$



(2) *There exist positive numbers* $z_1, \dots, z_n$ *such that*

$$\sum_{k=1}^{m} a_{ii}^k(t) z_i - \sum_{j=1,\, j \neq i}^{n} \sum_{k=1}^{m} \left| a_{ij}^k(t) \right| z_j \geq 1, \quad t \in [0, +\infty),$$

$i = 1, \dots, n.$

שימוש בתאוריה לתנועה אנכית. אי שוויונים למשתנים של משוואות דיפרנציאליות וזמן השהיה

$$1 \le \left(n_p p_4 M + n_{14} M - n_p p_1 + n_{11}\right) z_1 - \left|-n_p p_2 + n_{12}\right| z_2 - \left|-n_p p_3 + n_{13}\right| z_3 - \left|-n_p p_4 + n_{14}\right| z_5$$

$$1 \le n_{22} z_2 - \left|M n_{24} + n_{21}\right| z_1 - \left|n_{23} + b_0\right| z_3 - z_4 - \left|n_{24}\right| z_5$$

$$1 \le -b_0 z_3 - z_4$$

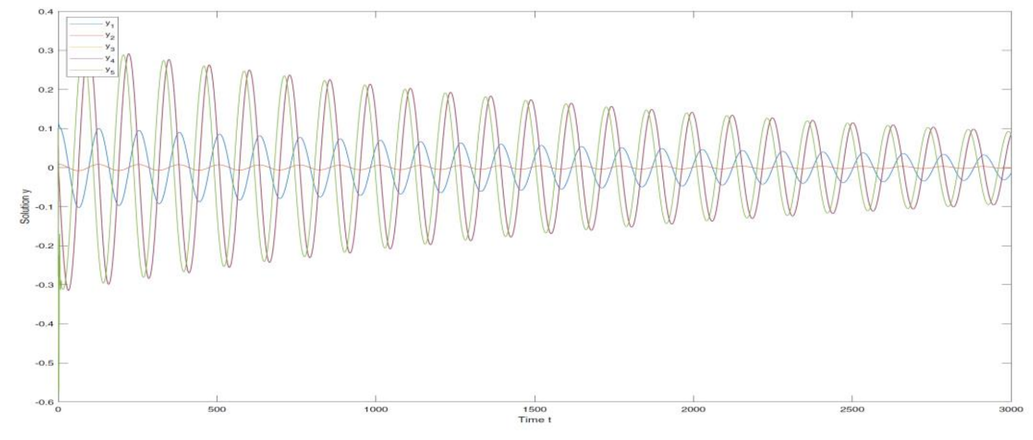
$$1 \le \left(b_0 + n_0 + n_{33}\right) z_4 - \left|n_B b_4 M - n_0 n_{24} M + M n_{34} - n_B b_1 - n_0 n_{21} - n_{21}\right| z_1 - \left|n_B b_2 - n_0 n_{22} + n_{32}\right| z_2 - \left|b_0^2 + n_0 b_0 + n_{33} b_0 + n_B b_3 + n_0 n_{23}\right| z_3 - \left|n_B b_4 - n_0 n_{24} + n_{34}\right| z_5$$

$$1 \le \left(-n_p p_4 M + n_{14} M\right) z_5 - \left|-M^2 n_p p_4 + M^2 n_{14} + M n_p p_1 - M n_{11} + n_{41}\right| z_1 - \left|-n_p p_2 M + M n_{12} + n_{42}\right| z_2 - \left|-n_p p_3 M + M n_{13} - n_{42}\right| z_3$$

$$\tau \le \frac{1}{e\left(n_{14} M + n_{11} - n_p \cdot p_1 - \left|n_p \cdot p_4 \cdot M\right|\right)}$$

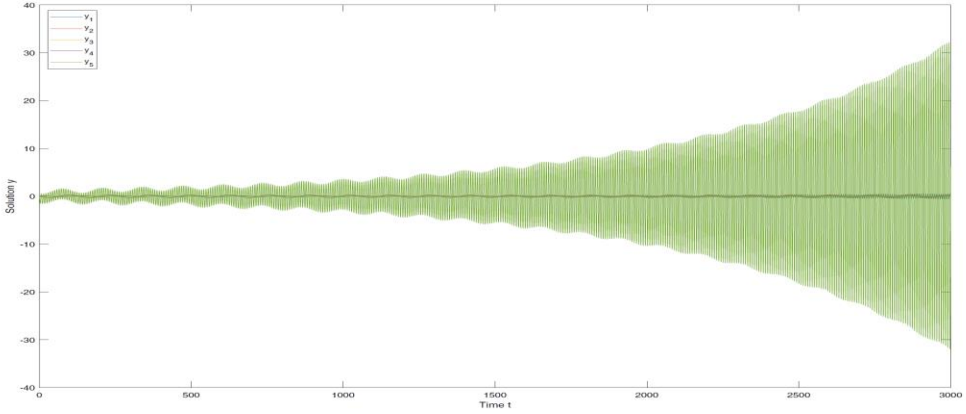
יציבות אקספוננציאלית של משתנים עבור תנועה אנכית

עם פרמטרים
נכונים מקבלים
יציבות
אקספוננציאלית.
פתרון שואף ל
.0



Numerical simulation of system (3.1) for time delay $\tau = 1$(unitless time), where $y_1(t) = v(t)$, $y_2(t) = \alpha(t)$, $y_3(t) = \vartheta(t)$, $y_4(t) = \varphi(t)$, $y_5(t) = \lambda(t)$

עם פרמטרים לא
נכונים פתרון מתבדר



Numerical simulation of system (3.1) for time delay $\tau = 2$(unitless time), where $y_1(t) = v(t)$, $y_2(t) = \alpha(t)$, $y_3(t) = \vartheta(t)$, $y_4(t) = \varphi(t)$, $y_5(t) = \lambda(t)$

Competitors

UAV Navigation
grupo oesía

SCIENTIFIC SYSTEMS

IAI

RAFAEL
ADVANCED DEFENSE SYSTEMS LTD.

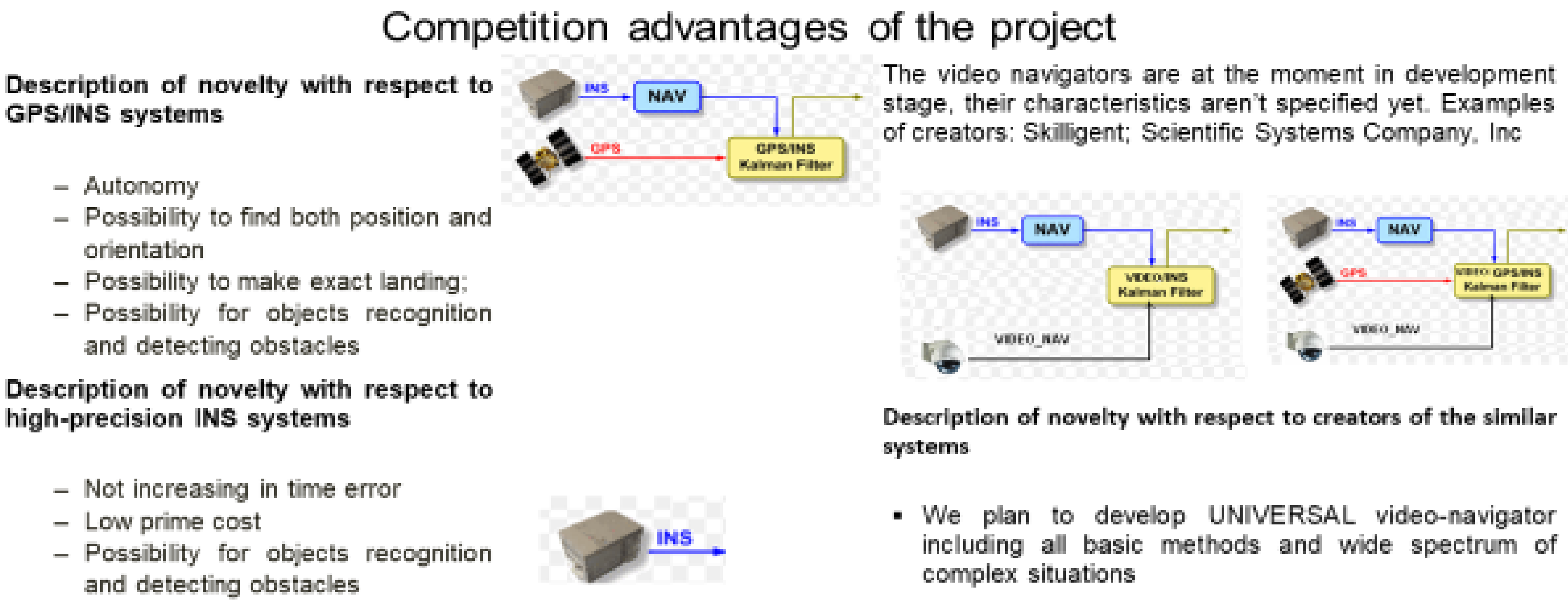
Elbit Systems

OFFICIAL TEAM
SPACEIL
TEAM SPACEIL

ASIO
TECHNOLOGIES

SIGHTEC

Competitive advantages of the project with respect to the other methods not using visual navigation



Competition advantages of the project

Description of novelty with respect to GPS/INS systems

- Autonomy
- Possibility to find both position and orientation
- Possibility to make exact landing;
- Possibility for objects recognition and detecting obstacles

Description of novelty with respect to high-precision INS systems

- Not increasing in time error
- Low prime cost
- Possibility for objects recognition and detecting obstacles

The video navigators are at the moment in development stage, their characteristics aren`t specified yet. Examples of creators: Skilligent; Scientific Systems Company, Inc

Description of novelty with respect to creators of the similar systems

- We plan to develop UNIVERSAL video-navigator including all basic methods and wide spectrum of complex situations

החדשנות

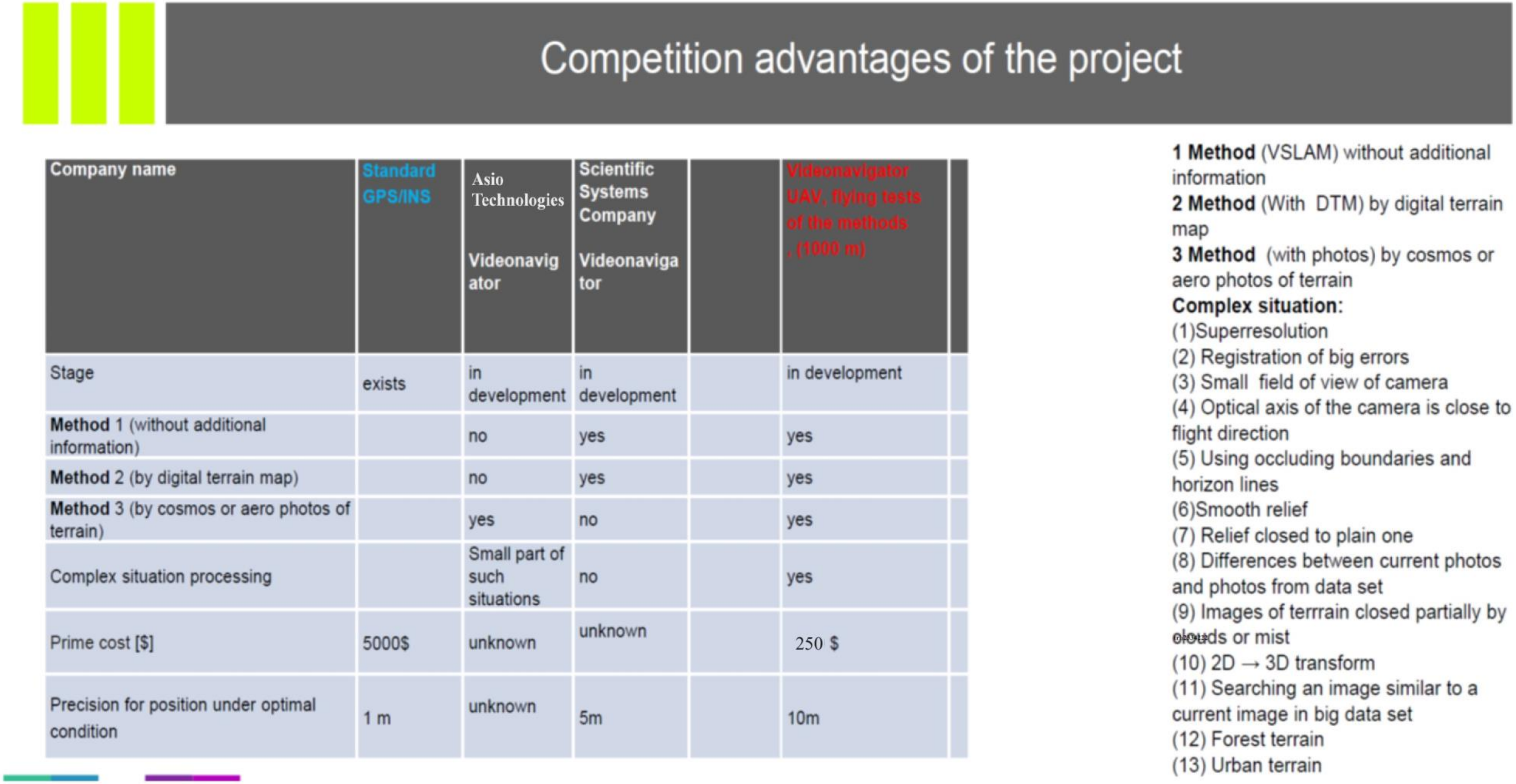
רקע טכנולוגי

Currently used GPS/INS methods are not trusty and are not noise-immune (easily suppressed) enough.

So, we plan to use vision-based navigation.

Contrary to the similar projects, we plan to use a big set of existing and new methods that allow us to get universality of our system – the system will operate in different complex environments for different optical systems with precision enough for successful drone navigation.

Competitive advantages of the project with respect



Competition advantages of the project

Company name	Standard GPS/INS	Asio Technologies Videonavigator	Scientific Systems Company Videonavigator		Videonavigator UAV, flying tests of the methods , (1000 m)	
Stage	exists	in development	in development		in development	
Method 1 (without additional information)		no	yes		yes	
Method 2 (by digital terrain map)		no	yes		yes	
Method 3 (by cosmos or aero photos of terrain)		yes	no		yes	
Complex situation processing		Small part of such situations	no		yes	
Prime cost [$]	5000$	unknown	unknown		250 $	
Precision for position under optimal condition	1 m	unknown	5m		10m	

1 Method (VSLAM) without additional information
2 Method (With DTM) by digital terrain map
3 Method (with photos) by cosmos or aero photos of terrain
Complex situation:
(1)Superresolution
(2) Registration of big errors
(3) Small field of view of camera
(4) Optical axis of the camera is close to flight direction
(5) Using occluding boundaries and horizon lines
(6)Smooth relief
(7) Relief closed to plain one
(8) Differences between current photos and photos from data set
(9) Images of terrrain closed partially by clouds or mist
(10) 2D → 3D transform
(11) Searching an image similar to a current image in big data set
(12) Forest terrain
(13) Urban terrain

Scientific Systems Company, Inc.
https://www.ssci.com/
Product: ImageNav™

Sightec
https://www.sightec.com
Product: NAVSIGHT

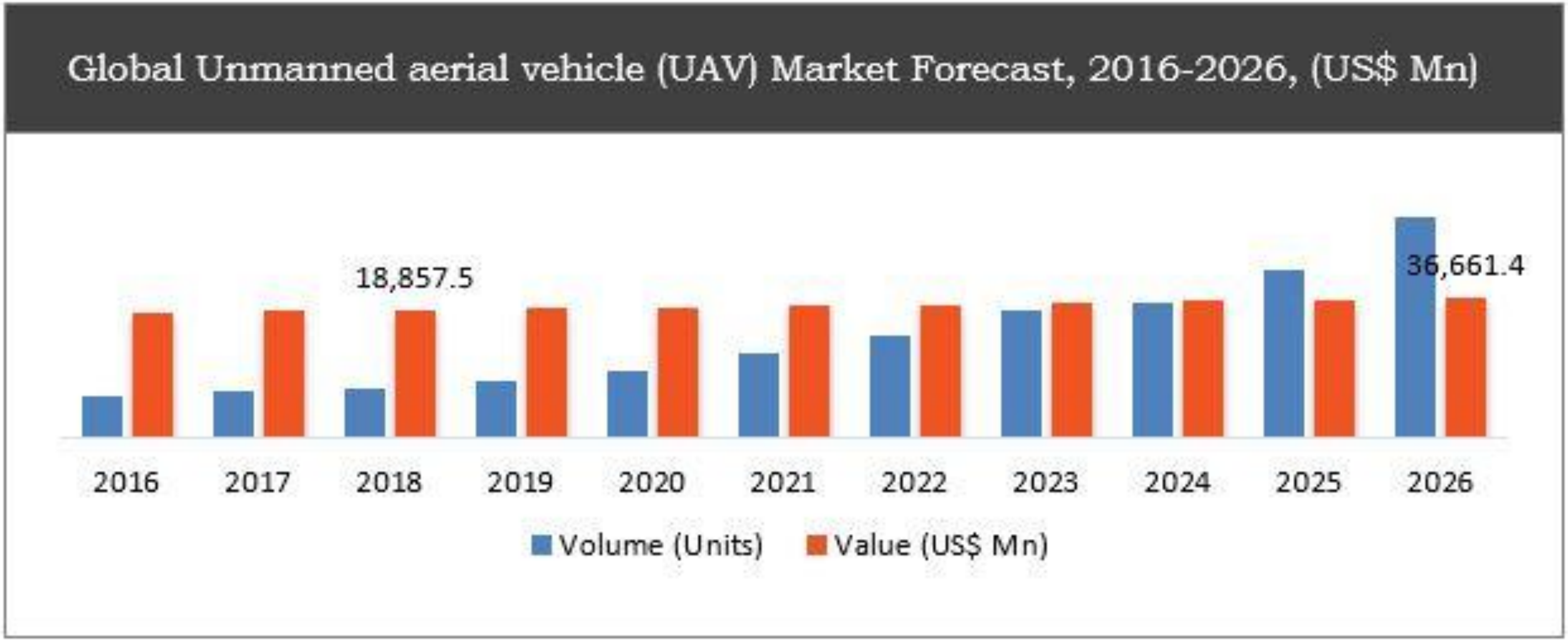
Asio Technologies
https://asiotech.com/
Product: NOCTA

UAV NAVIGATION
https://www.uavnavigation.com/
Product: VNS01

Novelty with respect to creators of the similar systems

- Universality for UAV (ALL basic methods and complex situations)

https://www.alltheresearch.com/report/140/unmanned-aerial-vehicle-market



קניין רוחני ופטנטים

Intellectual Property: Know-how

Current stage is Know-how. In future we plan patent registrations of a new and advanced drone navigation systems in the case of regular and complex operating environment

הצוות

Visual navigation specialist

Dr. Kupervasser Oleg, included to 30 issue of “Marquise Who’s Who in the world”, 17 years of experience (leading companies of Russia and Israel), 11 papers and conference reports

Optimal control theory specialist

Prof. Domoshnitsky Alexander
Mathematics Department of Ariel University,
has 30 years of experience, more than 120 publications, received 7 awards and grants

Simon Kogan, Ph D

Algorithm developer

Igor Dadashov, M Sc

Programmer, drone operator, Hardware specialist

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