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«_____»_____2023 .

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151 « , - »

" " _____ 2023 .

1. : « » 13.04.2023 . 507/
2. : 22.05.2023 25.06.2023 .
3. : -
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4. : ;
; ;

5. - :

/		-	-
1.		28.03.2023	
2.		08.05.2023	
3.		12.05.2023	
4.		14.05.2023	
5.	1.	17.05.2023	
6.	2.	23.05.2023	
7.	3.	25.05.2023	
8.	4.	31.05.2023	
9.		05.06.2023	

6. : «__» _____ 2023 .

: _____ . .

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: 60 ., .49, .4
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 (), (), ().

.....	6
1.	8
1.1.	8
1.2.	11
1.3.	16
2.	25
2.1	25
2.2	27
2.2.1	27
2.2.2	29
2.2.3	31
2.3	32
2.3.1	32
2.3.2	36
2.4 Matlab.....	39
3.	45
3.1	45
3.2	50
3.3	51
3.4	51
3.5 FreeIMU.....	52
3.6	53
4.	55
.....	61
.....	62

() -

				23.09.00.000			
<i>Виконав.</i>	<i>Єфремов О. О.</i>				<i>Літ.</i>	<i>Арк.</i>	<i>Аркушів</i>
<i>Керівник</i>	<i>Мельник Ю. В.</i>					6	62
<i>Консульт.</i>	<i>Мельник Ю. В.</i>				151-301-		
<i>Контрол.</i>	<i>Мельник Ю. В.</i>						
<i>Зав. каф.</i>	<i>Мельник Ю. В.</i>						

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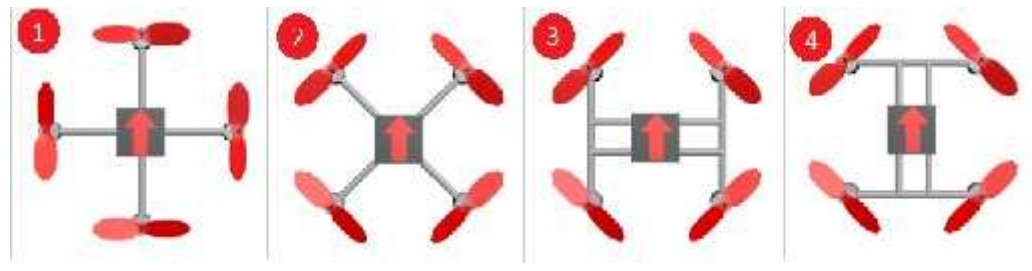
1.1.

(.. Multicopter) –

(.. Quadrocopter)-

6

. 1.



. 1.

1 2, 3 4,

1 2

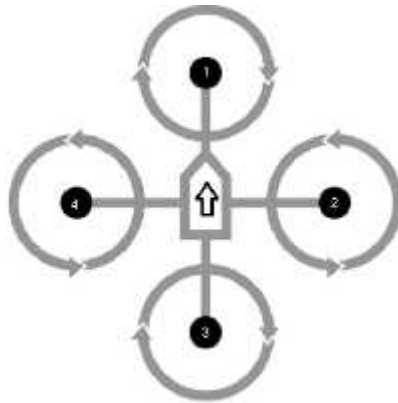
				23.09.00.000		
Виконав.	Єфремов О. О.			Літ.	Арк.	Аркушів
Керівник	Мельник Ю. В.				8	62
Консульт.	Мельник Ю. В.			151-301-		
Контрол.	Мельник Ю. В.					
Зав. каф.	Мельник Ю. В.					

2

1

1,

.2.



.2.

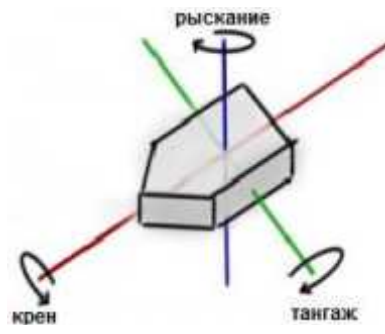
(.3):

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) -

);

) -



. 3.

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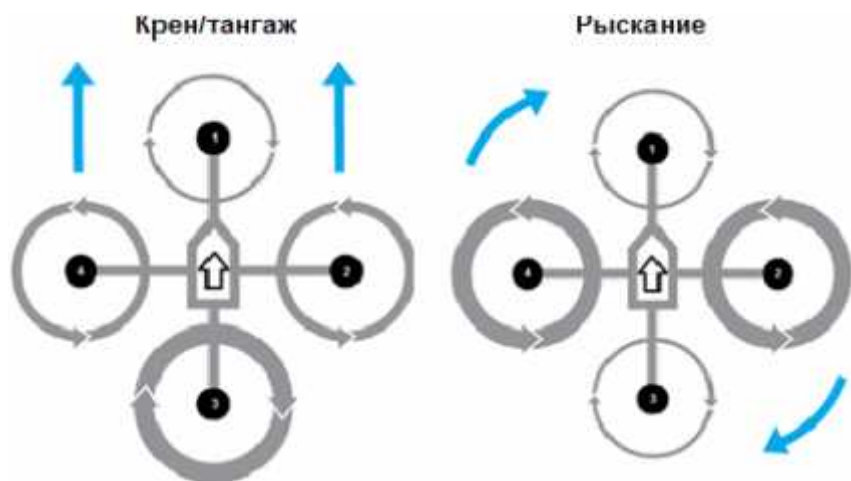
4.).

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. 4.

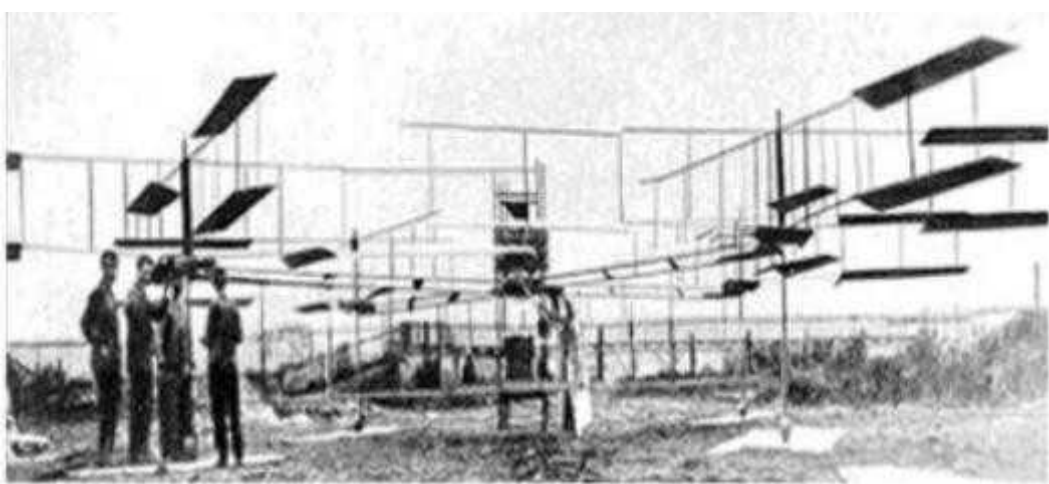
/

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GPS ..).
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1.2.

(.5)

1908



. 5.

1920

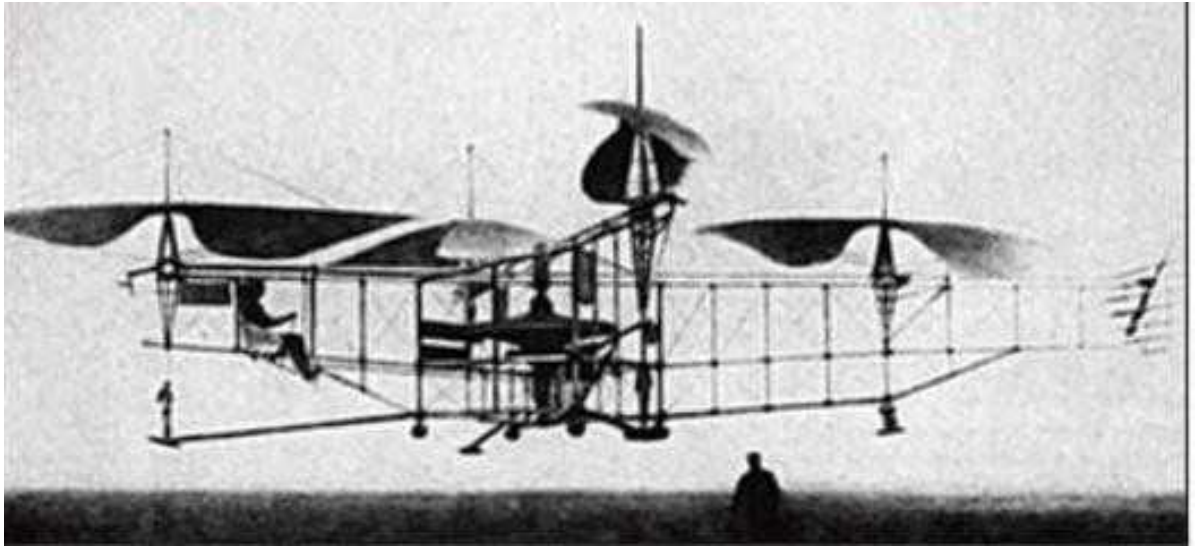
25 ..,

125 . . ’

1923

, 14 1924
360 .

.6.



.6.

1922

1,7 .

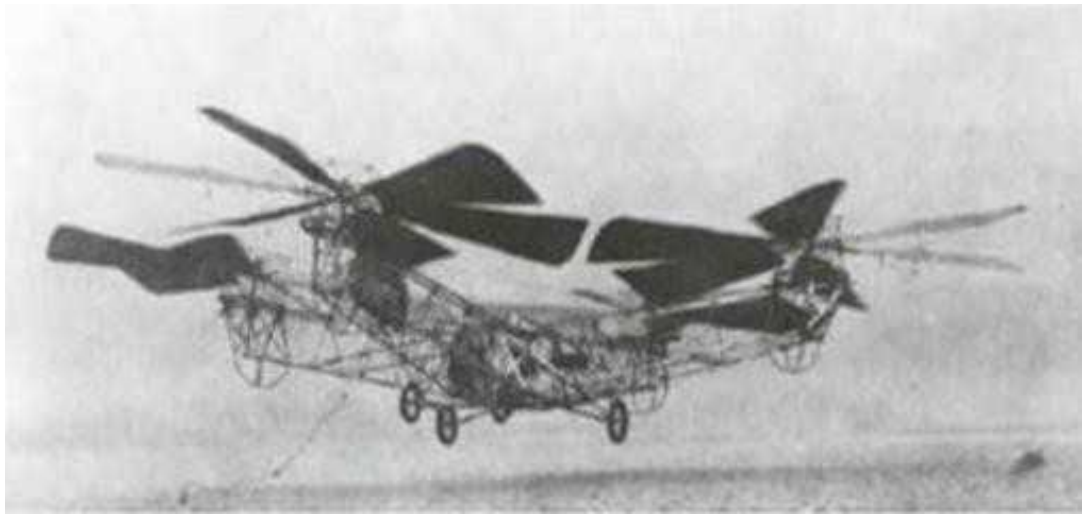
220 . .

, (.7)

1,8

1

42 .

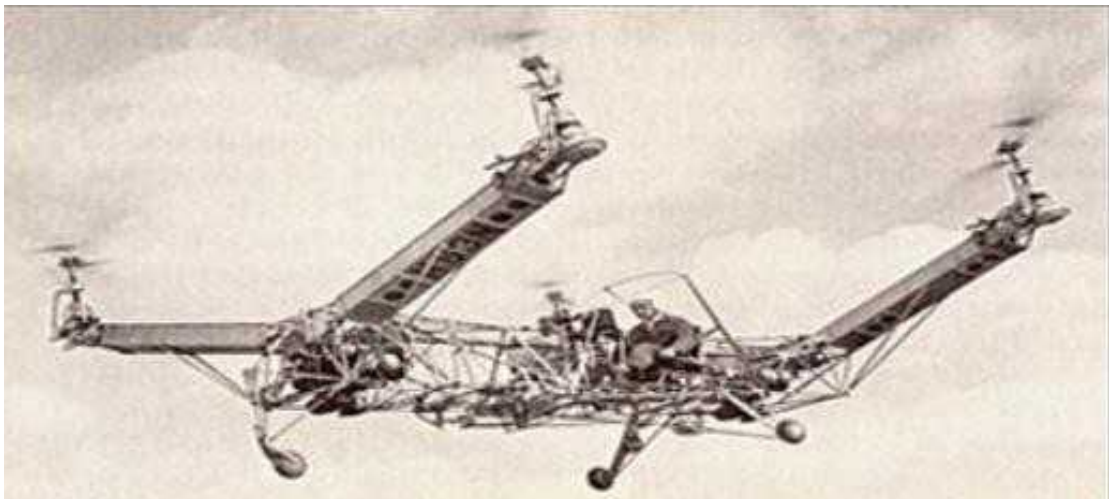


. 7.

1955

« »

Convertawing



. 8.

Convertawing

1958

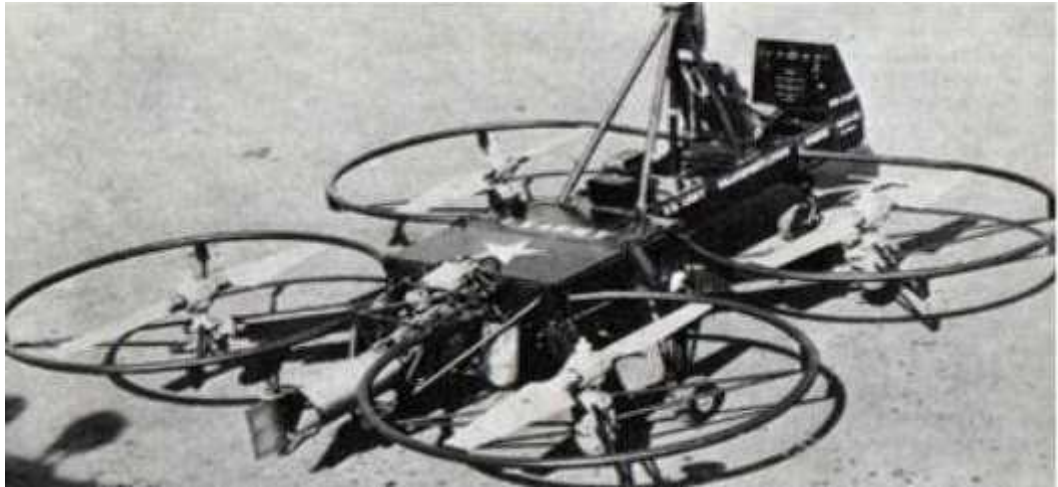
Curtiss-

Wright

VZ-7.

-

. 9.



. 9.

VZ-7

Curtiss-Wright

-

-

-

-

-

Parrot AR (. 10).

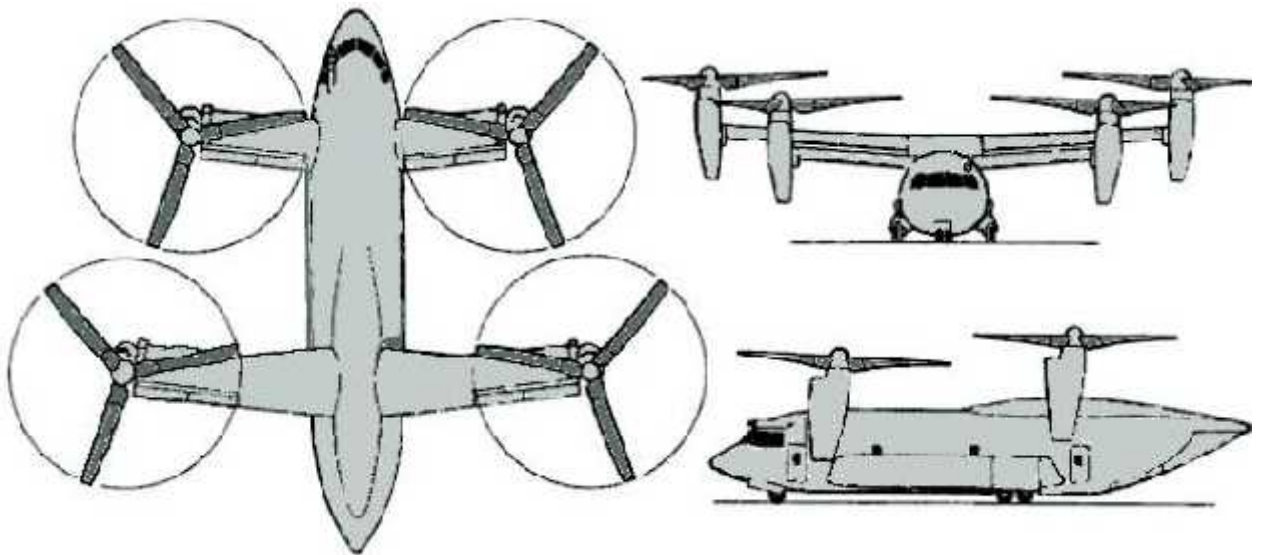
-



.10.

Parrot AR

Bell Boeing QTR, Boeing. , . 11. -
 , -
 90% 15 .



. 11.

Bell-Boeing

1.3.

Arduino Mega 2560

Arduino –

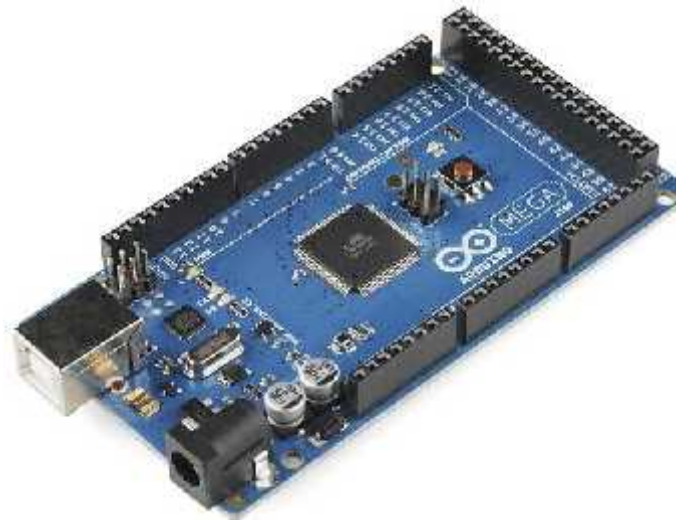
(..) ++

Arduino Uno,

Uno

Mega (.12).

. 1.



. 12. Arduino Mega 2560

Mega Uno

	Arduino Mega	Arduino Uno
	ATmega2560	ATmega328
()	16	16
()	5	5
(.)	54	54
(.)	16	6
(.)	15	6
Flash	256	32
EEPROM	4	1
SRAM	8	2
(.)	6	2

GY-88

GY-88 (. 13),

, I2C :

-) MPU-6050- ;
-) HMC5883L – ;
-) BMP085 – .



.13. *GY-88*

MPU-6050 6

16 ,

: $\pm 250, \pm 500, \pm 1000, \pm 2000 \frac{\circ}{\text{сек}}$ $\pm 2g, \pm 4g, \pm 8g, \pm 16g$

HMC5883L,

$\pm 0.88, \pm 1.3, \pm 1.9, \pm 2.5, \pm 4.0, \pm 4.7, \pm 5.6, \pm 8.1$

BMP085

30-110

) 0,5 ;

) 0,25 ;

) 0,1 .

GY-88 :

) Vin – 5 ;

) 3,3 V – ;

) GND – ;

) SCL – I2C;

) SDA – I2C;

) M_DRDY – HMC5883L;

) G_ADO – I2C MPU-6050;

) G_INT – MPU-6050.

4 : Vin, GND, SDA SCL.

60

)
)
)
)
)

90%;

2212 (. 14).



. 14.

2212

-) : 22 ;
-) : 12 ;
-) : 1000;
-) : 80%;
-) 4-10 : > 75%;
-) : 0,5 ;
-) : 27,5 30 ;
-) : 3,17 ;
-) : 47 .

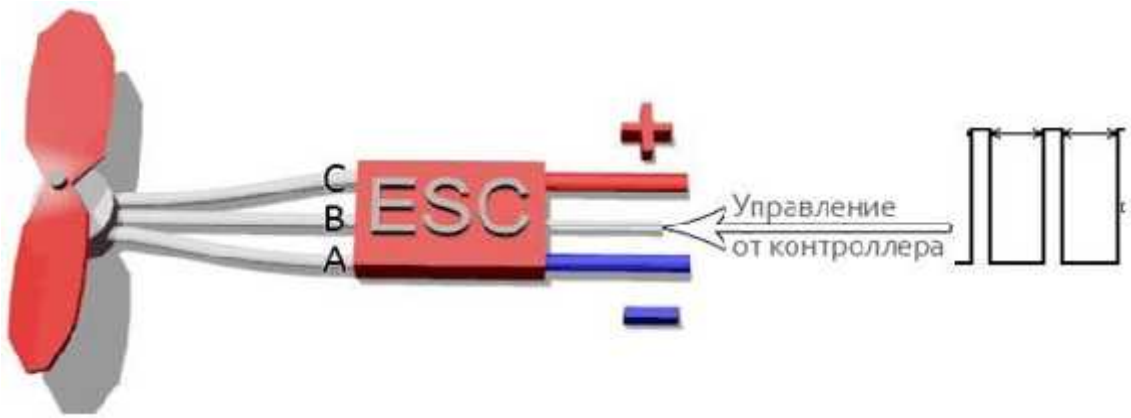
,
800 . 0,96 ,
-

(.. ESC – Electronic Speed Controll) -

, , , -
- , -
,

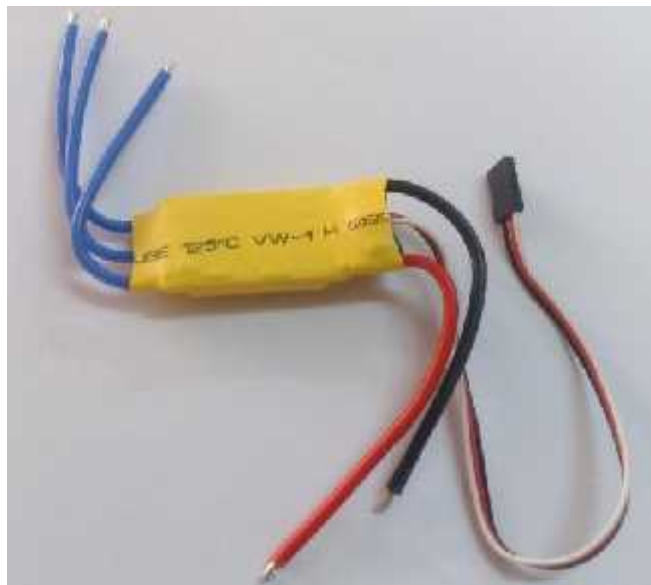
1000-2000 .

. 15. -



. 15.

- Hobbysky (. 16), :
-) - 30 (40 10);
 -) - 5,5-12,6 ;
 -) - 1 /5V;
 -) - 25 .



. 16.

Hobbysky

-
(. 17)

:

WFT07

-) 7 ;
-) 2,4 ;
-) 800 ;
-) 3,7-6 .



. 17. WFT07

WFR07S,

(. 18) :

-) 2,4 – 2,483 ;
-) 4096 ;
-) 4,8 – 6 .



. 18. WFR07S

, -
 10 4,5.
 (254) 4,5 (114) (.19).



. 19.

HJ450 (. 20),

) 282 . ;
)

450 .



. 20. HJ450

LiPo HRB (. 21)

:

-) : 11,1 ;
-) : 2200 / ;
-) : 66 ;
-) : 3 3,7 ;
-) : 182 ;
-) : 102 34 22



. 21. HRB

, 6-9 , -

2.1

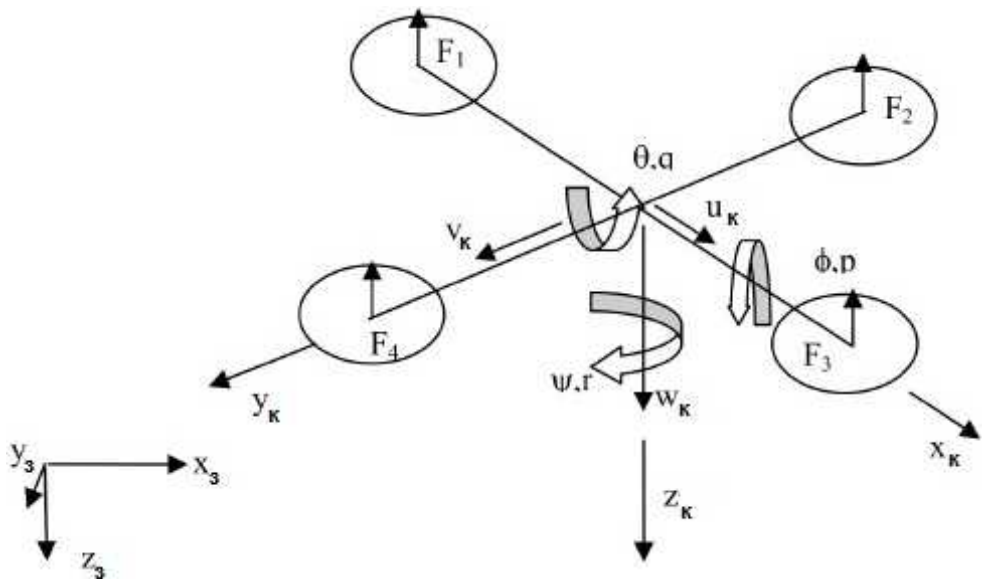
East-Down),

NED (. North-

. 22.

23.09.00.000

Виконав.	Єфремов О. О.			2.	Літ.	Арк.	Аркушів
Керівник	Мельник Ю. В.					25	62
Консульт.	Мельник Ю. В.				151-301-		
Контрол.	Мельник Ю. В.						
Зав. каф.	Мельник Ю. В.						



. 22.

$\theta, \psi, \varphi.$

p, q r.

u, v w.

$F_i.$

3 3 -

$$R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) \\ 0 & -\sin(\phi) & \cos(\phi) \end{bmatrix}$$

$\theta,$:

$$R_y = \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{bmatrix}$$

$\psi,$:

$$R_z = \begin{bmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

z-y-x

$$D = R_z R_y R_x$$

$$D = \begin{bmatrix} \cos(\theta)\cos(\psi) & \cos(\theta)\sin(\psi) & -\sin(\theta) \\ \sin(\phi)\sin(\theta)\cos(\psi) + \cos(\phi)\sin(\psi) & \sin(\phi)\sin(\theta)\sin(\psi) + \cos(\phi)\cos(\psi) & \sin(\phi)\cos(\psi) \\ \cos(\phi)\sin(\theta)\cos(\psi) - \sin(\phi)\sin(\psi) & \cos(\phi)\sin(\theta)\sin(\psi) - \sin(\phi)\cos(\psi) & \cos(\phi)\cos(\theta) \end{bmatrix}$$

2.2

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = D^{-1} \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

$$\begin{bmatrix} q \\ r \end{bmatrix} = E \begin{bmatrix} \theta \\ \dagger \end{bmatrix}$$

$$E = \begin{bmatrix} 1 & 0 & -\sin(\theta) \\ 0 & \cos(\theta) & \sin(\theta)\cos(\theta) \\ 0 & -\sin(\theta) & \cos(\theta)\cos(\theta) \end{bmatrix}$$

$$\begin{bmatrix} \theta \\ \dagger \end{bmatrix} = E^{-1} \begin{bmatrix} q \\ r \end{bmatrix}$$

2.2.1

$$F = m * V$$

m -

V -

V , , -
:

$$F = m * V + \omega * m * V$$

ω -

:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = m \begin{bmatrix} \dot{u} & p & u \\ \dot{v} & q & v \\ \dot{w} & r & w \end{bmatrix}$$

:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = m \begin{bmatrix} \dot{u} & q & w & r & v \\ \dot{v} + r * u - p * w & & & & \\ \dot{w} & p & v & q & u \end{bmatrix}$$

, ;

)
)

W .

F

:

$$\begin{bmatrix} W_x \\ W_y \\ W_z - T \end{bmatrix} = m \begin{bmatrix} \dot{u} & q & w & r & v \\ \dot{v} + r * u - p * w & & & & \\ \dot{w} & p & v & q & u \end{bmatrix}$$

:

$$\begin{bmatrix} 0 \\ 0 \\ m * g \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ T \end{bmatrix} = m \begin{bmatrix} \dot{u} & q & w & r & v \\ \dot{v} + r * u - p * w & & & & \\ \dot{w} & p & v & q & u \end{bmatrix}$$

,

:

$$\dot{u} = r * v - q * w - g * \sin(\theta)$$

$$\dot{v} = p * v - r * u + g * \cos(\theta) \sin(\phi)$$

$$\dot{w} = q * u - p * v + g * \cos(\phi) \cos(\theta) - \frac{T}{m}$$

:

$$T = b(f_1^2 + f_2^2 + f_3^2 + f_4^2)$$

f_i -
 b -

;

:

$$\dot{u} = r * v - q * w - g * \sin(\theta)$$

$$\dot{v} = p * v - r * u + g * \cos(\theta) \sin(\phi)$$

$$\dot{w} = q * u - p * v + g * \cos(\phi) \cos(\theta) - \frac{b}{m}(f_1^2 + f_2^2 + f_3^2 + f_4^2)$$

2.2.2

:

$$M = \dot{H}$$

-

;

-

,

:

$$M = \dot{H} + \omega * H$$

:

$$H = I * \omega$$

I -

;

ω -

.

,

,

:

$$I = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix}$$

I_x, I_y, I_z -

$$M = I * \omega + \omega * I * \omega$$

$$M_x = \dot{p} \cdot I_x + q \cdot r (I_z - I_y)$$

$$M_y = \dot{q} \cdot I_y + p \cdot r (I_x - I_z)$$

$$M_z = \dot{r} \cdot I_z + p \cdot q (I_y - I_x)$$

$$, \quad I_x = I_y, \quad :$$

$$M_x = \dot{p} \cdot I_x + q \cdot r (I_z - I_y)$$

$$M_y = \dot{q} \cdot I_y + p \cdot r (I_x - I_z)$$

$$M_z = \dot{r} \cdot I_z$$

:

$$M_x = l \cdot b (f_2^2 - f_4^2)$$

$$M_y = l \cdot b (f_1^2 - f_3^2)$$

$$M_z = d (f_2^2 + f_4^2 - f_1^2 - f_3^2)$$

d -

;

1 -

:

$$\dot{p} = \frac{l \cdot b}{I_x} (f_2^2 - f_4^2) - q \cdot r \frac{I_z - I_y}{I_x}$$

$$\dot{q} = \frac{l \cdot b}{I_y} (f_1^2 - f_3^2) - p \cdot r \frac{I_x - I_z}{I_y}$$

$$\dot{r} = \frac{d}{I_z} (f_2^2 + f_4^2 - f_1^2 - f_3^2)$$

2.2.3

$$\begin{aligned}
 M_x &= \dot{p} \cdot I_x + q \cdot r(I_z - I_y) + \dot{H}_x + H_z \cdot q - H_y \cdot r \\
 M_y &= \dot{q} \cdot I_y + p \cdot r(I_x - I_z) + \dot{H}_y + H_x \cdot r - H_z \cdot p \\
 M_z &= \dot{r} \cdot I_z + \dot{H}_z + H_y \cdot p - H_x \cdot q
 \end{aligned}$$

H_x, H_y, H_z -

$$\begin{aligned}
 H_x &= \sum_{i=1}^4 I_{xi} \cdot \omega_{xi} \\
 H_y &= \sum_{i=1}^4 I_{yi} \cdot \omega_{yi} \\
 H_z &= \sum_{i=1}^4 I_{zi} \cdot \omega_{zi}
 \end{aligned}$$

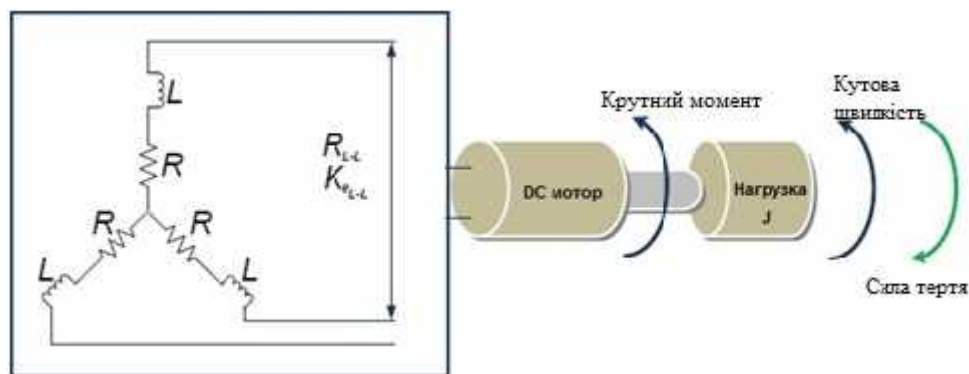
$$\begin{aligned}
 M_x &= \dot{p} \cdot I_x + q \cdot r(I_z - I_y) + H_z \cdot q \\
 M_y &= \dot{q} \cdot I_y + p \cdot r(I_x - I_z) - H_z \cdot p \\
 M_z &= \dot{r} \cdot I_z + \dot{H}_z
 \end{aligned}$$

$$\begin{aligned} \dot{p} &= \frac{l \cdot D}{I_x} (\dot{\varphi}_2^2 - \dot{\varphi}_4^2) - q \cdot r \frac{I_z - I_y}{I_x} + \frac{H_z}{I_x} q \\ \dot{q} &= \frac{l \cdot b}{I_y} (\dot{\varphi}_1^2 - \dot{\varphi}_3^2) - p \cdot r \frac{I_x - I_z}{I_y} - \frac{H_z}{I_y} p \\ \dot{r} &= \frac{d}{I_z} (\dot{\varphi}_2^2 + \dot{\varphi}_4^2 - \dot{\varphi}_1^2 - \dot{\varphi}_3^2) + \frac{\dot{H}_z}{I_z} \end{aligned}$$

2.3

2.3.1

. 23.



23.

R – ;
L – ;

$$G(s) = \frac{\frac{1}{K_e}}{r_m \cdot r_e \cdot s^2 + r_m \cdot s + 1}$$

$$T_m = \frac{3 \cdot R}{K_e \cdot K_t} - ;$$

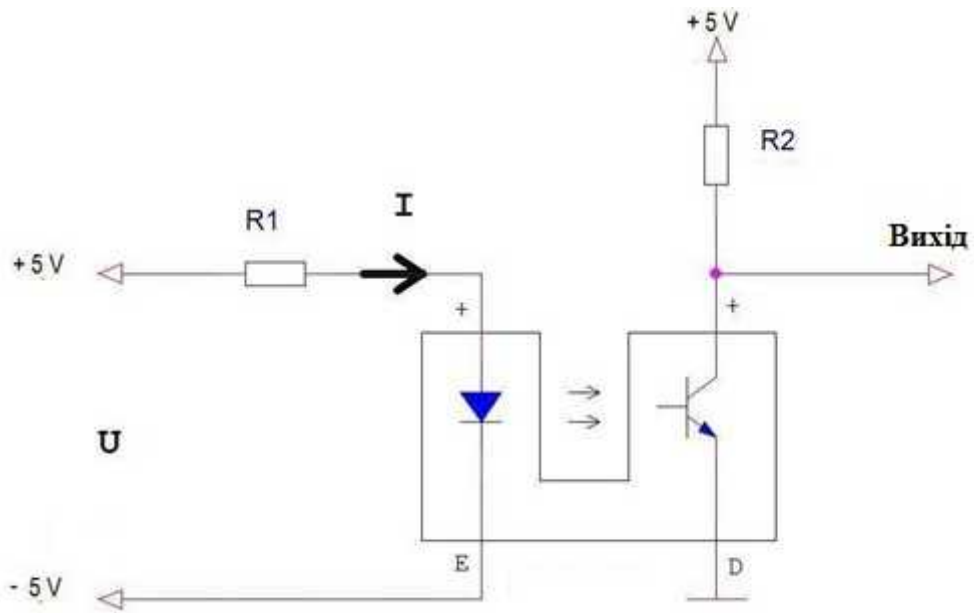
T_e -

$$K_e = \frac{K_e(L-L)}{\sqrt{3}}$$

K_e :

$$K_t = 0,0605 * K_e$$

(. 24),



24.

Matlab

ident

R1

25

R2 -

5

0.

1.

per minute)

(. RPM – revolutions

$$Rl = \frac{60}{2} * \frac{10^6}{ti}$$

ti -
.25

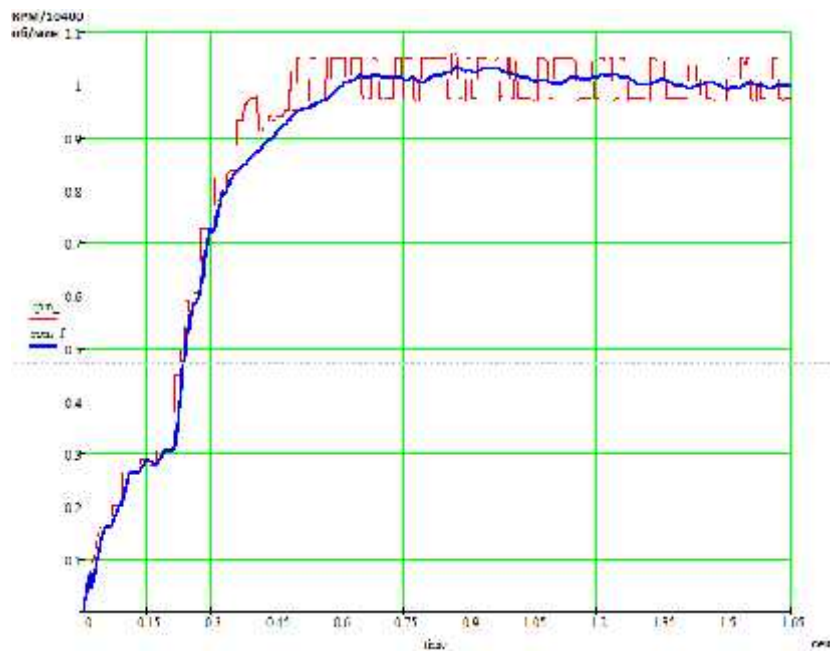
7-

0,5

40

$$y(k) = \frac{1}{n} \sum_{i=k-n+1}^k x_i^f$$

n -



25.

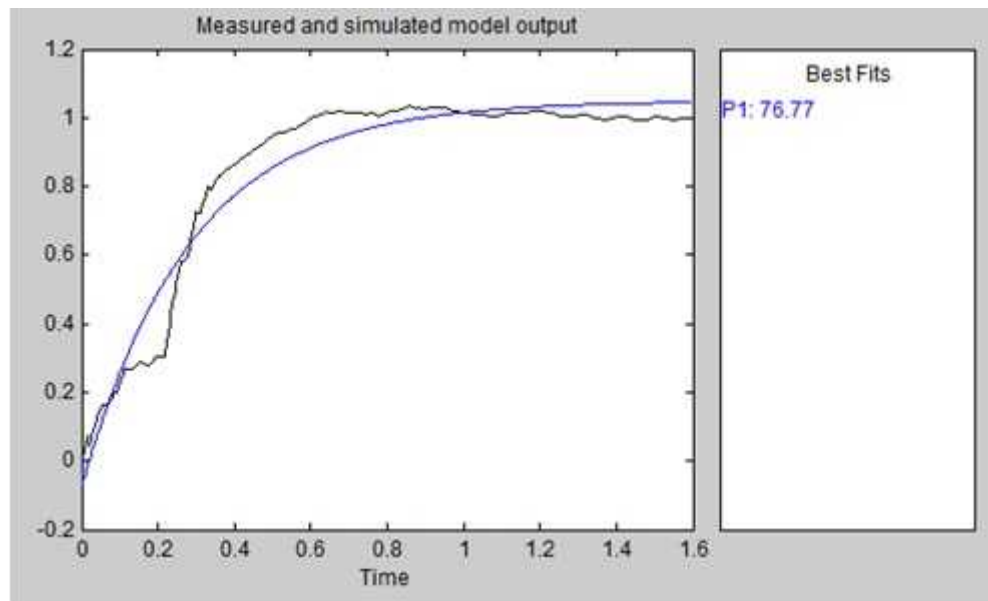
Matlab,

:

$$W = \frac{K}{T \cdot s + 1} = \frac{1.0491}{0.249s + 1}$$

. 26

System Identification Toolbox



26.

4000 / ..

/ :

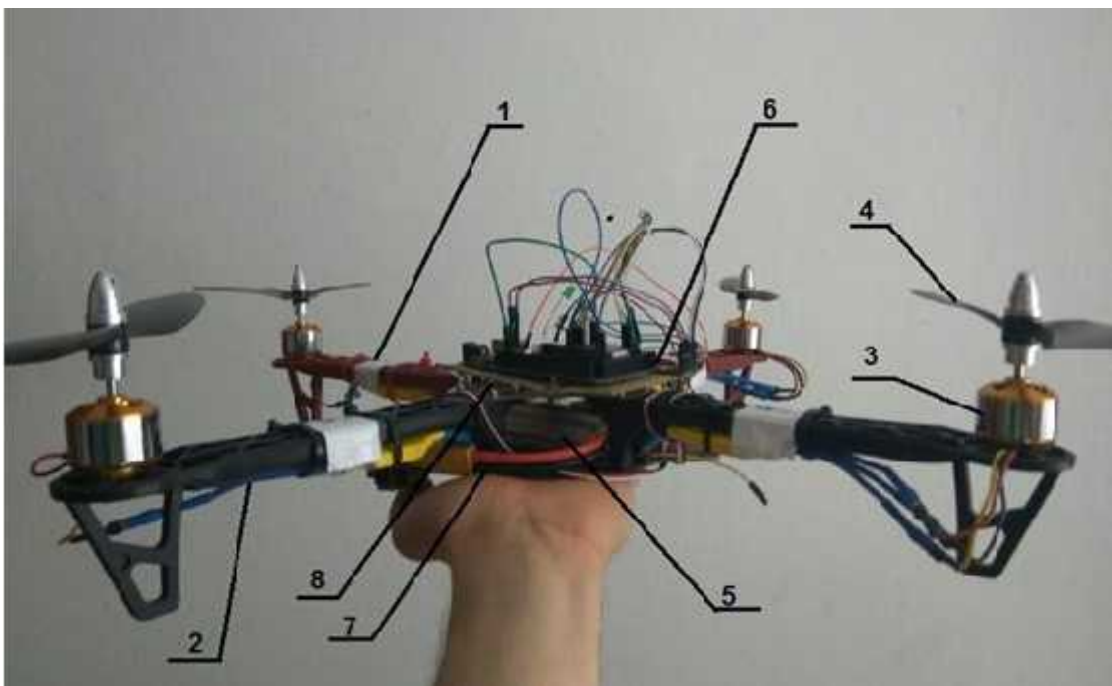
$$f = \frac{Rl * 2\pi}{60} = 418.88$$

:

$$b = \frac{m * g}{4 * f^2} = 0.96 * 1.3978 * 10^{-5} = 1.3418 * 10^{-5}$$

2.3.2

(.27).



27.

-) 2 ;
-) 4 ;
-) 4 ;
-) 1 ;
-) 1 Arduino Mega;
-) 1 1 .

()
 -), :
 « J -
 J_c ,
 m d ».

$$J = J_c + m * d^2$$

,
 , 2, -
 , .
2

			()	()	()
1			0.095	l=0.196 w=0.03 h=0.015	$d_x=0$ $d_y=0.132$ $d_z=0.132$
2			0.095	l=0.196 w=0.03 h=0.015	$d_x=0.132$ $d_y=0$ $d_z=0.132$
3			0.06	r=0.01375 h=0.03	$d_x=0.02$ $d_y=0.235$ $d_z=0.235$
4			0.008	r=0.127 h=0.01	$d_x=0.05$ $d_y=0.235$ $d_z=0.235$

5			0.179	$l=0.102$ $w=0.034$ $h=0.022$	$d_x=0.015$ $d_y=0.015$ $d_z=0$
6	Arduino mega		0.064	$l=0.102$ $w=0.053$ $h=0.01$	$d_x=0.01$ $d_y=0.01$ $d_z=0$
7			0.027	$l=0.125$ $w=0.125$	$d_x=0.005$ $d_y=0.005$ $d_z=0$
8			0.038	$l=0.18$ $w=0.125$	$d_x=0.025$ $d_y=0.025$ $d_z=0$
			0.96		

m
28).

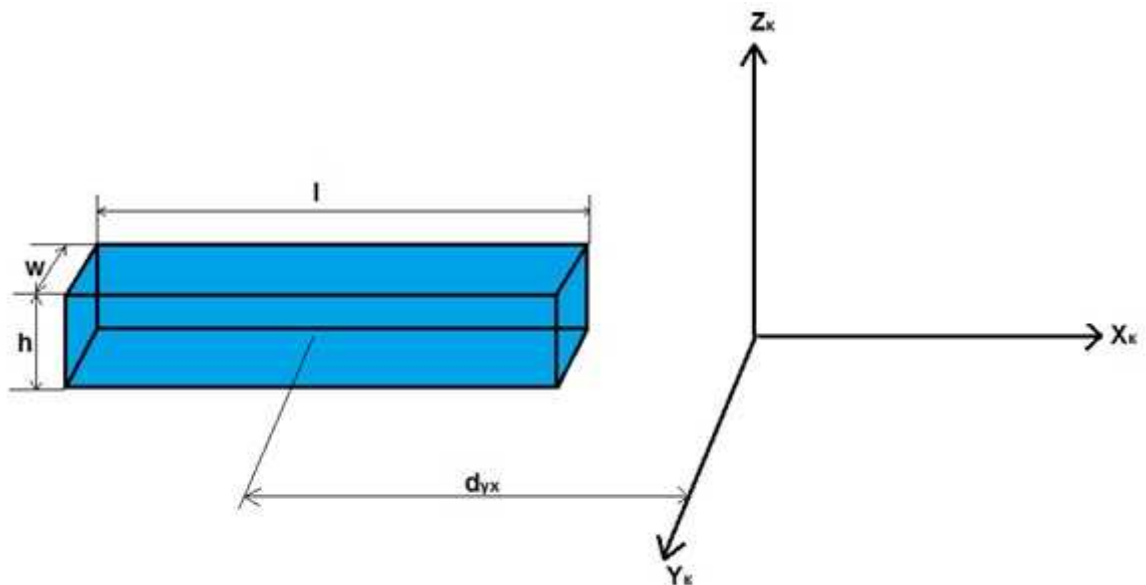
d

l ,

w ,

h

(.



28.

2.4

Matlab

Simulink

. 31.

6DOF

Aerospace Blockset.

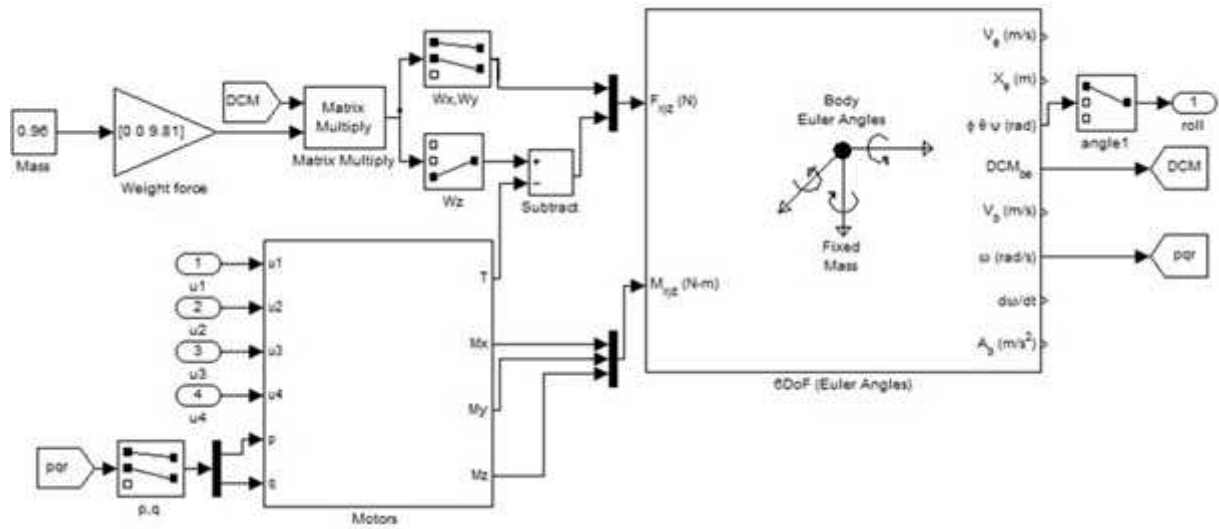
g ,

X, Y Z.

DCM

p, q, r ,

θ, ϕ та ψ

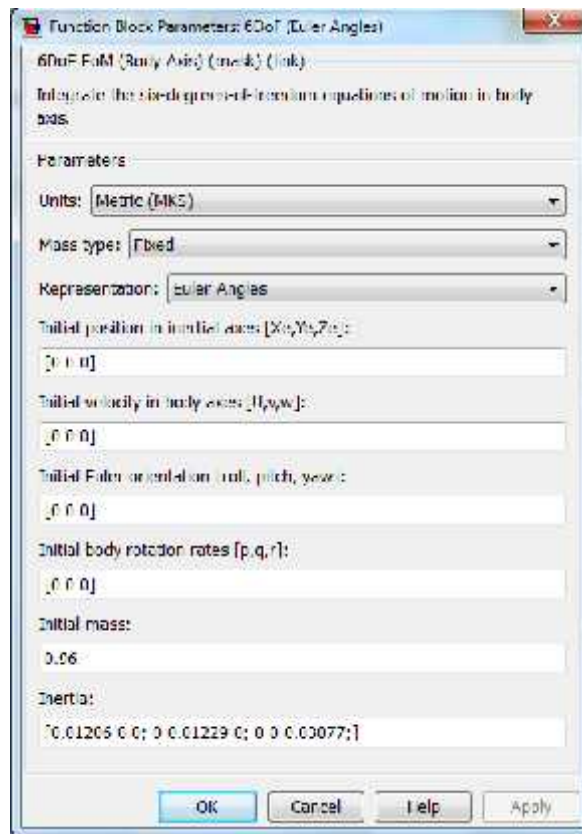


31.

Simulink

6DOF

. 32.



31.

6DOF

Motors (. 33)

q ,

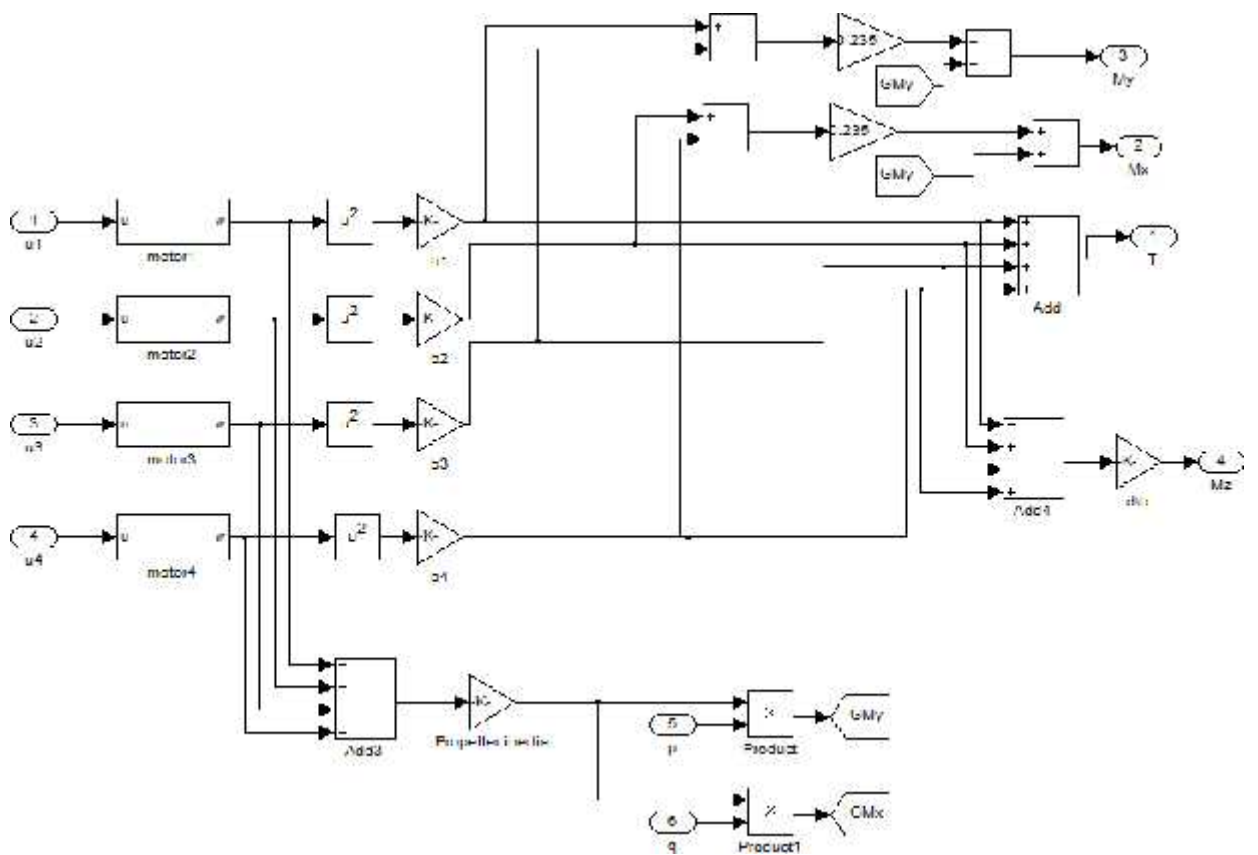
X Y.

p ,

M_x M_y ,

G_x G_y .

M_z .



33.

Simulink

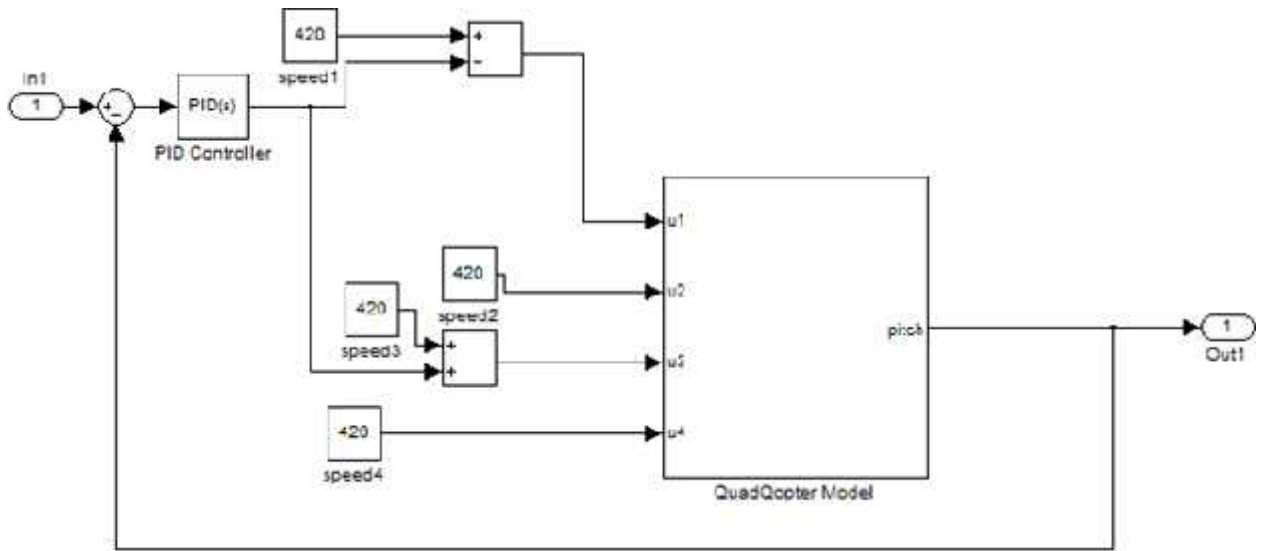
PID

$u(t)$

$$u(t) = P + I + D = K_p * s(t) + K_i * \int_0^t s(\tau) * d + K_d * \frac{a}{d},$$

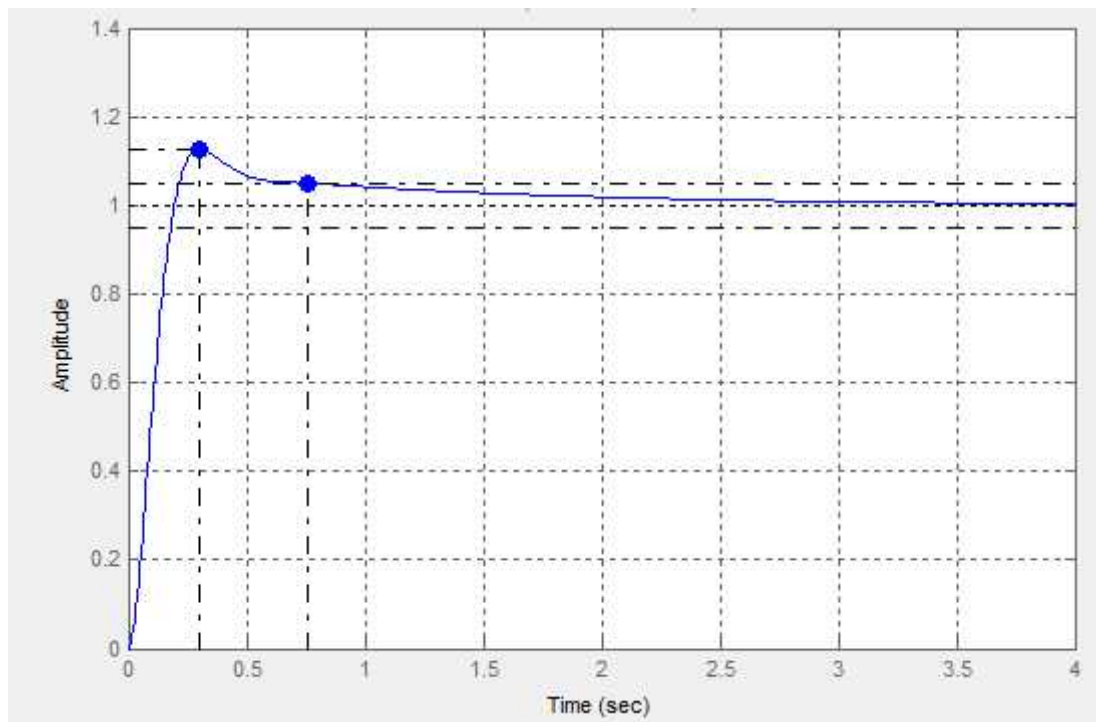
K_p, K_i, K_d -

34.



34.

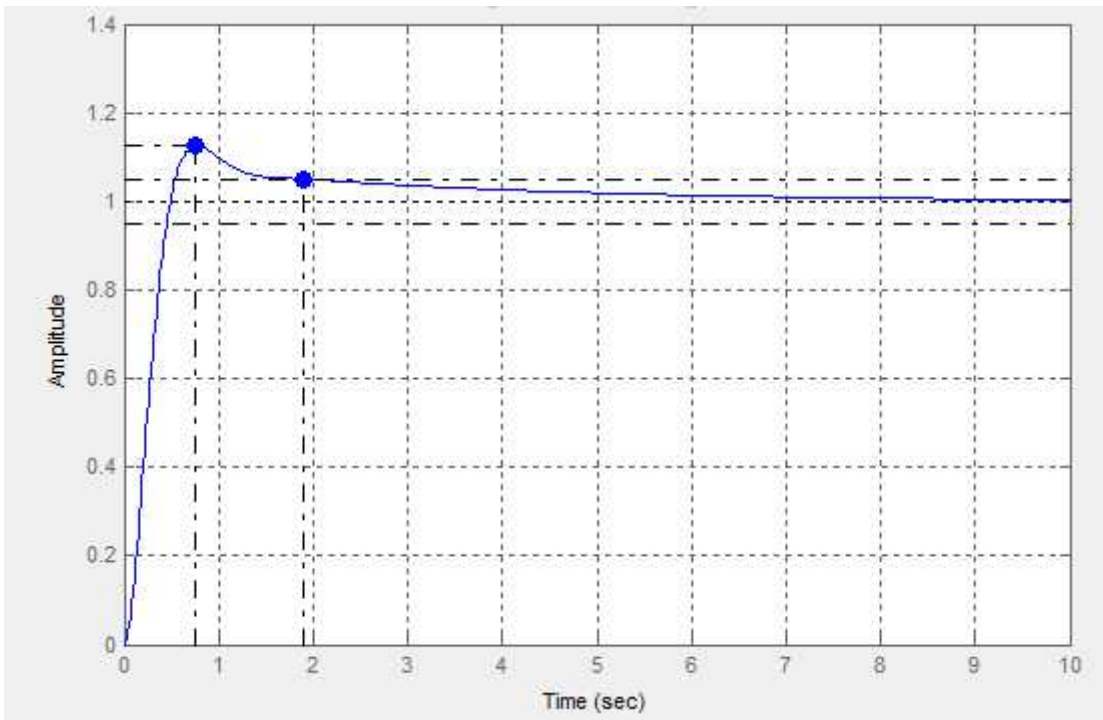
. 35.



35.

$$I_x \quad I_y$$

. 36.



. 36.

. 3.

3

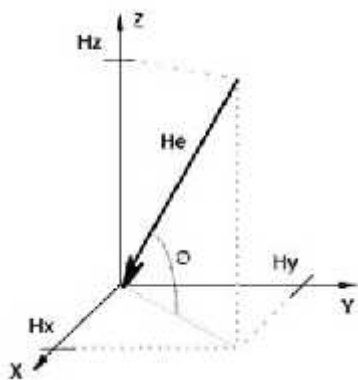
0.78419	0.44572	0.14634
0.77651	0.46121	0.14072
1.12940	0.42964	0.24746

: , -
Simulink -

, 1-2 -

3.1

– X, Y, Z, . 37.



. 37.

$$H_e = \sqrt{H_x^2 + H_y^2 + H_z^2}$$

Z- $H_z = 0,$

$$H_e = \varphi - \frac{180}{\pi} * a \quad \frac{H_x}{H_y}$$

$H_e = 90,$ $H_y > 0,$ $H_e = 270,$ $H_y < 0.$

, $H_y = 0, H_e = 180$ ($H_x < 0$) $H_e = 0$ ($H_x > 0$).

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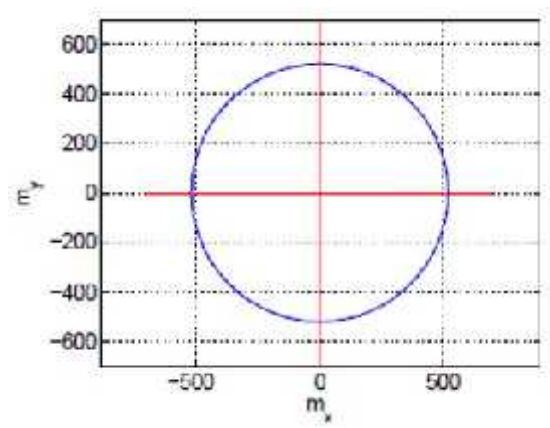
Виконав.	Єфремов О. О.			3.	Літ.	Арк.	Аркушів
Керівник	Мельник Ю. В.					45	62
Консульт.	Мельник Ю. В.				151-301-		
Контрол.	Мельник Ю. В.						
Зав. каф.	Мельник Ю. В.						

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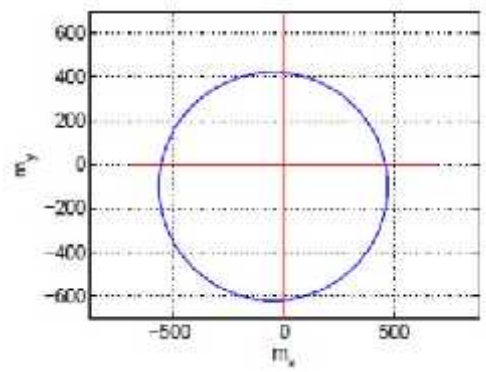
. 38

Z



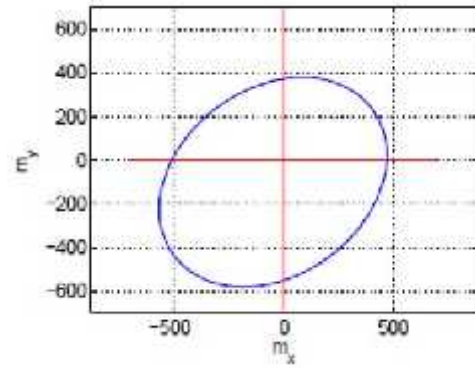
38.

. 39.



39.

.40.



40.

$$M \begin{bmatrix} C_1 & C_2 & C_3 & H_x - C_{10} \\ C_4 & C_5 & C_6 & H_y - C_{11} \\ C_7 & C_8 & C_9 & H_z - C_{12} \end{bmatrix}$$

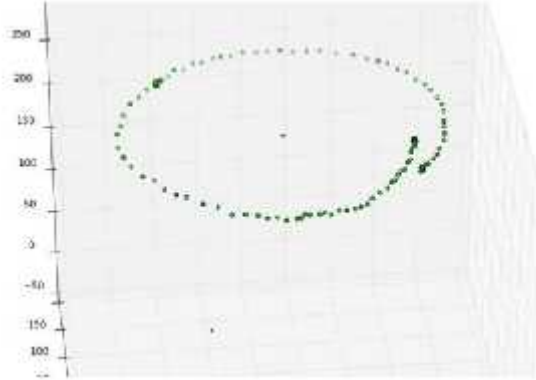
C_i ,

Arduino

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360

(.41).



41.

360

1.

P_{i1} P_{i2} .

180

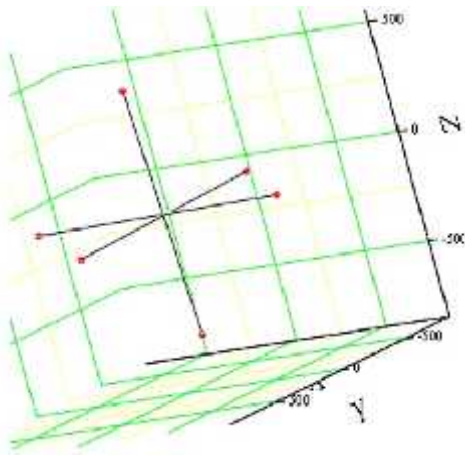
$$P_{i1} = (X, Y, Z), P_{i2} = (X, Y, Z)$$

2.

$$P_{c1} = \frac{P_{i1} + P_{i2}}{2}$$

3.

(.42).



42.

4.

5.

3 3.

6.

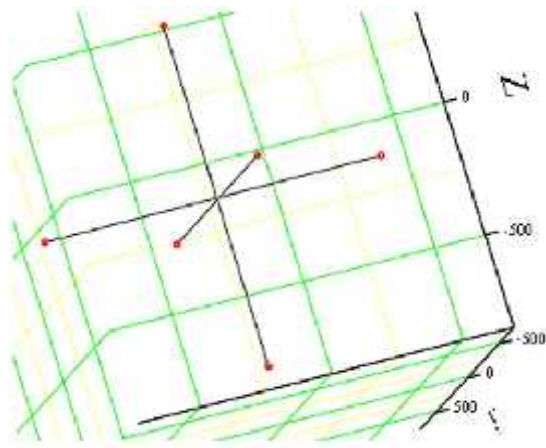
1.

2.

$$X_c = \frac{P_c + P_c}{2}$$

$$B = \frac{X_{c1} + X_{c2} + X_{c3}}{3}$$

. 43.



43.

3.2

$$\phi = \text{atan} \left(\frac{a_y}{a_z} \right)$$

$$\theta = \text{asin} \left(\frac{a_x}{g} \right)$$

a_x, a_y, a_z -
 g -

$$\Phi = \int_0^t r(r) dr$$

$$\phi[n] = \phi[n-1] + h \cdot r$$

h -
 r -

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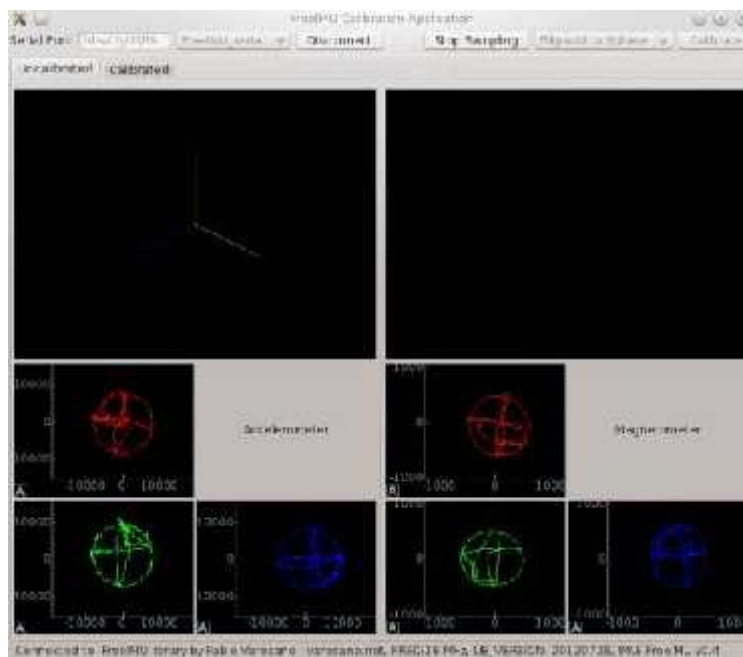
3.5 FreeIMU

FreeIMU,

GY-

88

(. 44).



3.6

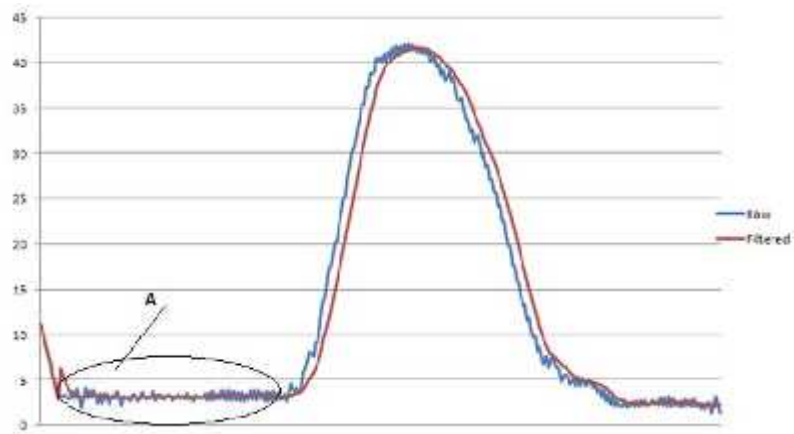
FreeIMU

0,75.

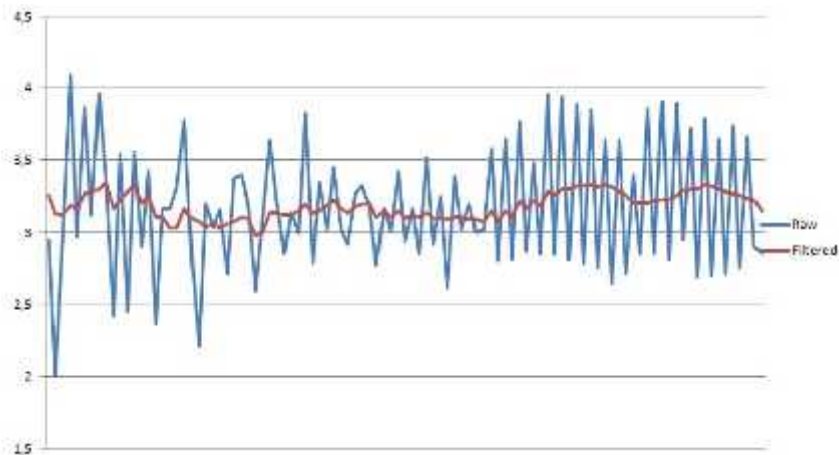
FreeIMU.

15-

(.45-46).



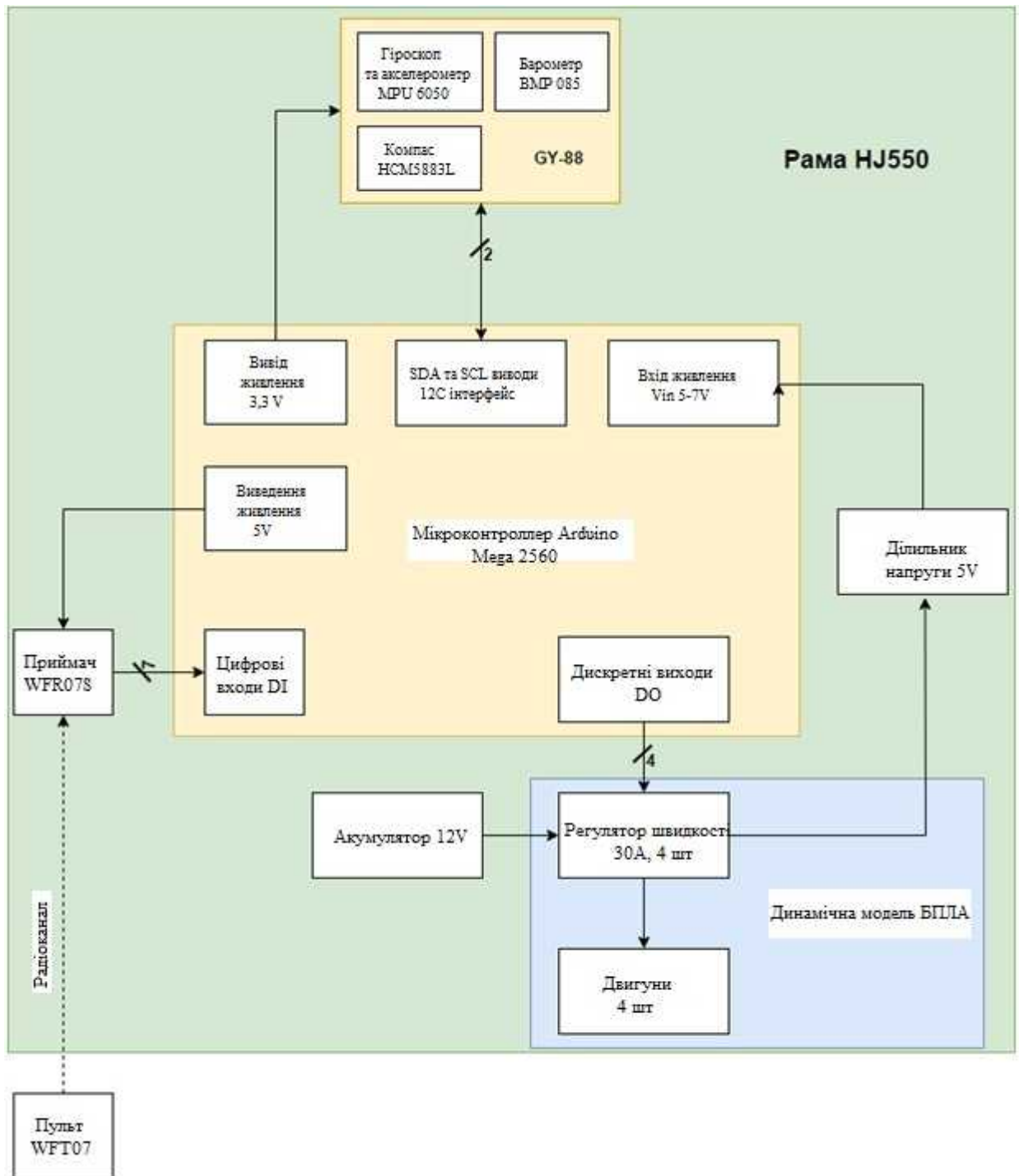
45.



46.

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Керівник	Мельник Ю. В.							55	62
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Контрол.	Мельник Ю. В.								
Зав. каф.	Мельник Ю. В.								

Arduino Mega 2560

12

GY

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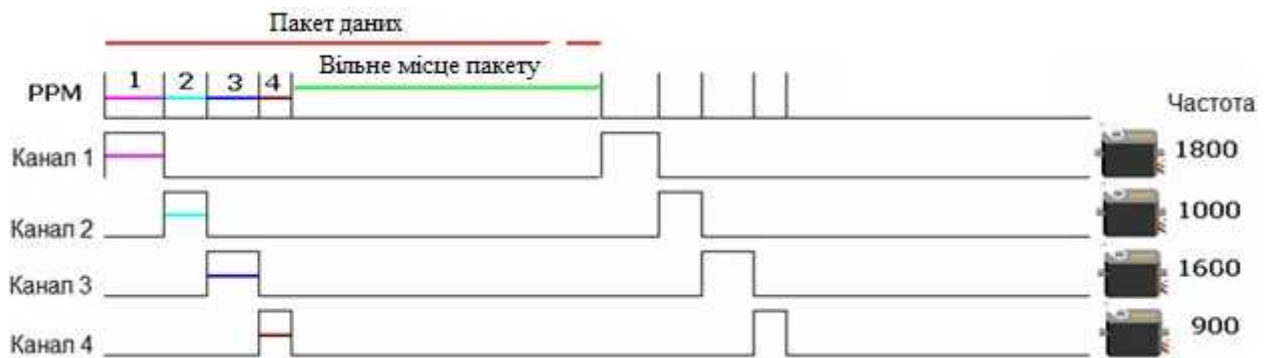
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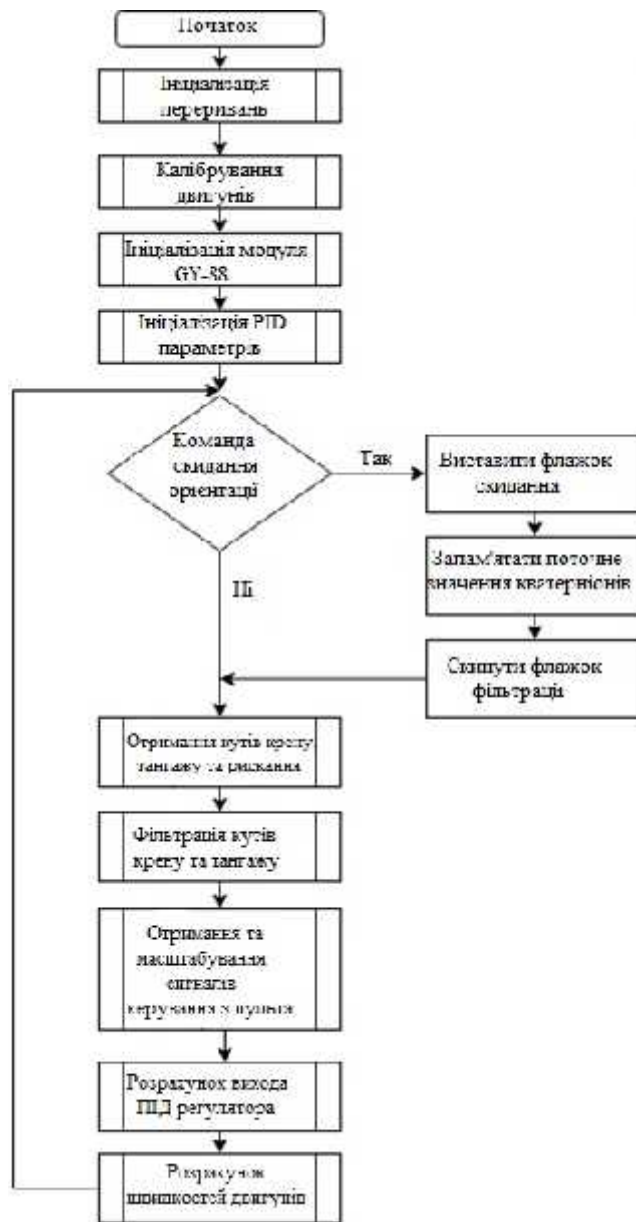
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3.4.

$$\begin{aligned}
 q_0 &= a_0 \cdot q_0 - a_1 \cdot q_1 - a_2 \cdot q_2 - a_3 \cdot q_3 \\
 q_1 &= a_0 \cdot q_1 + a_1 \cdot q_0 + a_2 \cdot q_3 - a_3 \cdot q_2 \\
 q_2 &= a_0 \cdot q_2 - a_1 \cdot q_3 + a_2 \cdot q_0 + a_3 \cdot q_1 \\
 q_3 &= a_0 \cdot q_3 + a_1 \cdot q_1 - a_2 \cdot q_1 + a_3 \cdot q_0
 \end{aligned}$$

a_i - , , .
 q_i - .

-) - 0-70 %;
-) -20-20;
-) - 20-20;
-) - 180-180.

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 . 30% 70% -
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0.8	0.65	0.15

0.82	0.45	0.15
1.5	0.5	0.3

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				23.09.00.000			
<i>Виконав.</i>	<i>Єфремов О. О.</i>				<i>Літ.</i>	<i>Арк.</i>	<i>Аркушів</i>
<i>Керівник</i>	<i>Мельник Ю. В.</i>					61	62
<i>Консульт.</i>	<i>Мельник Ю. В.</i>				151-301-		
<i>Контрол.</i>	<i>Мельник Ю. В.</i>						
<i>Зав. каф.</i>	<i>Мельник Ю. В.</i>						

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