

Trabalho de Graduação
Departamento de Engenharia Mecatrônica
Universidade de Brasília

Modelamento, Construção, Instrumentação, Localização,
Simulação e Controle de um Veículo Aéreo
Não-Tripulado do Tipo
Quadrirrotor

Pedro Henrique de Rodrigues Quemel e Assis Santana
phrqas@yahoo.com.br

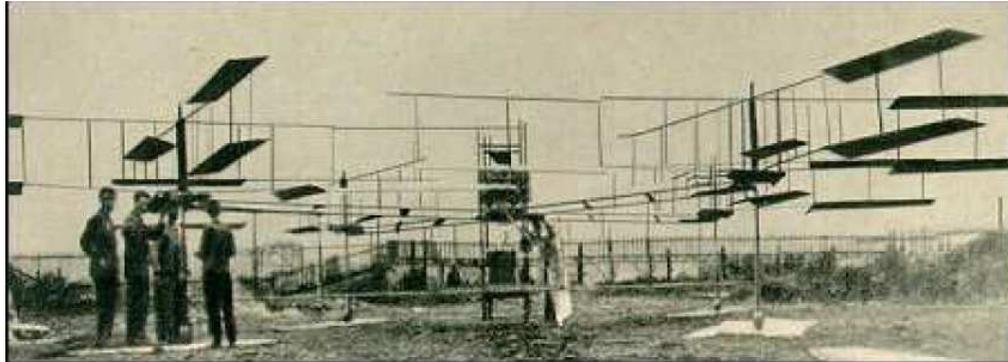
Marcelo Antunes Braga
braga.marcelo@gmail.com

Sumário



1. Introdução;
2. Desenvolvimento do protótipo;
3. Modelamento matemático;
4. Localização;
5. Controle;
6. Conclusões e propostas para trabalhos futuros.

1. Introdução



Giroplano N°1



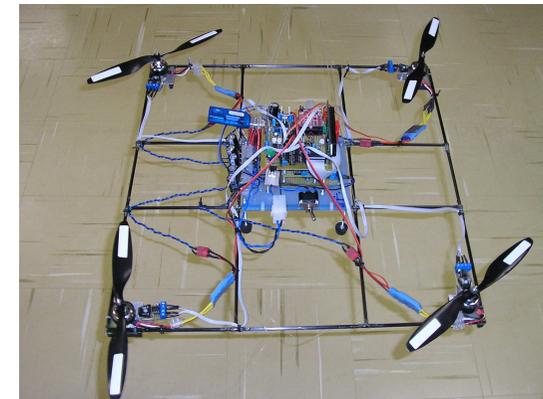
Draganflyer X-Pro



Quadrirrotor OS4

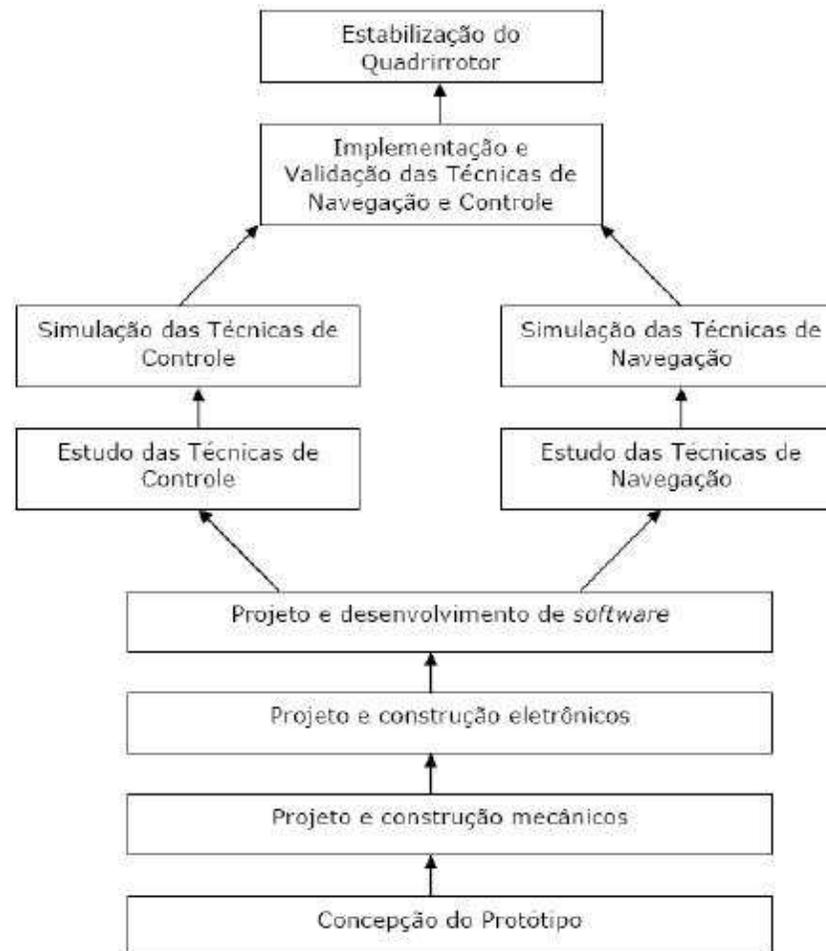


Projeto da CEA



Quadrirrotor do LARA
(ainda anônimo)

1. Introdução



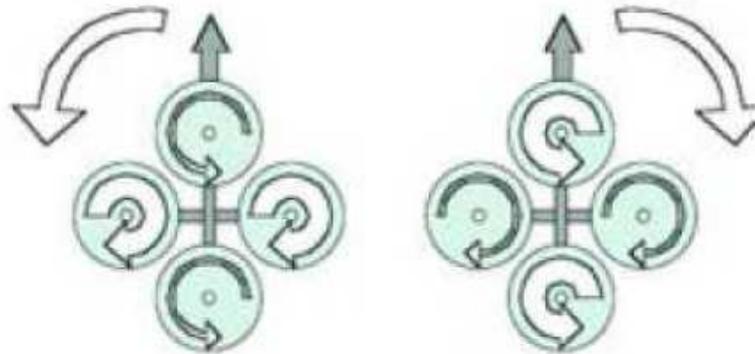
1. Introdução



Brasília, 09 de julho de 2008

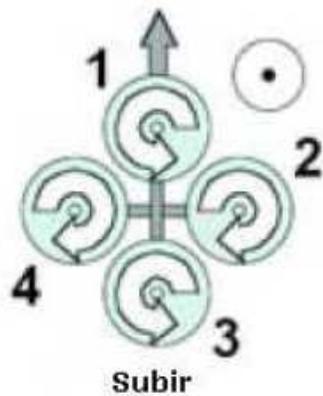
P.H.R.Q.A. Santana, M.A. Braga

1. Introdução

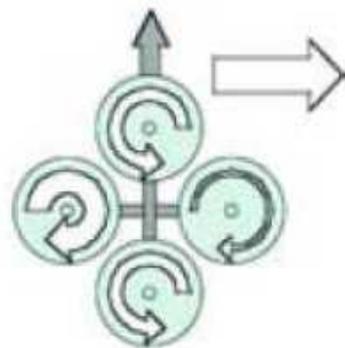


Rotação anti-horária

Rotação horária



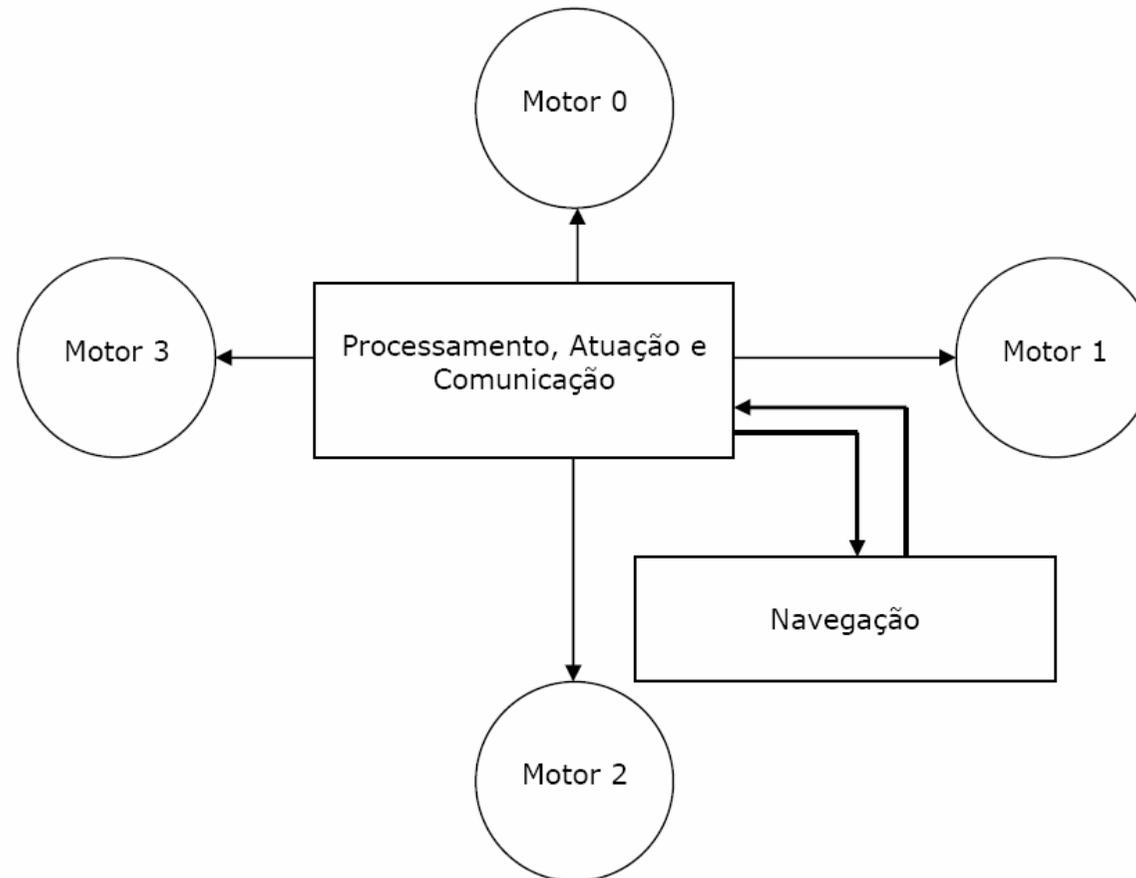
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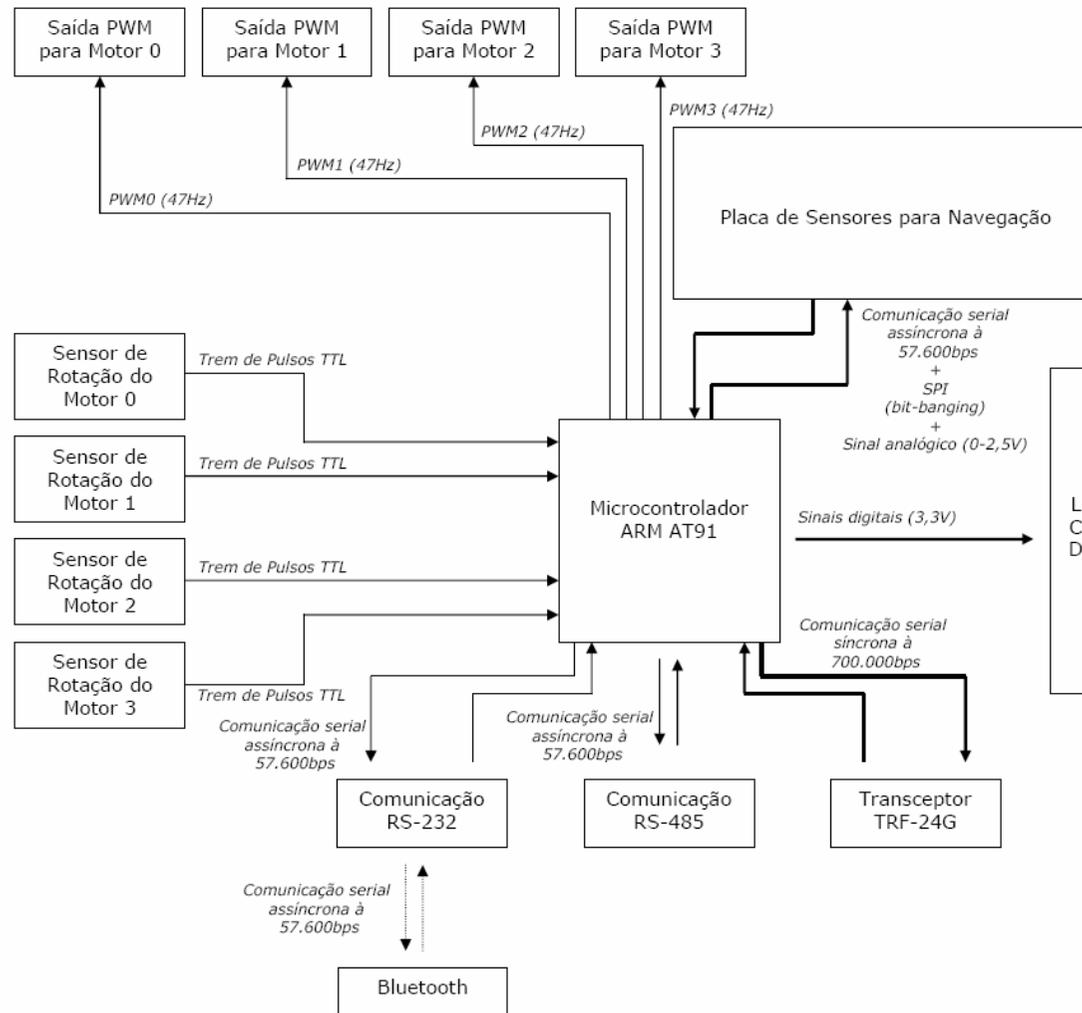
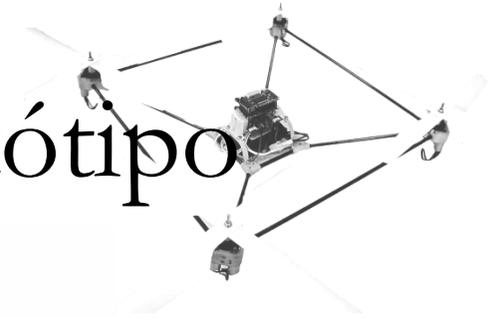
Virar à direita

Vantagens	Desvantagens
Mecânica simplificada (hélices de pás fixas)	Grande tamanho e peso.
Grande carga útil	Grande consumo de energia.
Efeitos giroscópicos reduzidos	Menor eficiência das hélices.
Maior segurança para operar próximo a obstáculos	
Boa manobrabilidade	

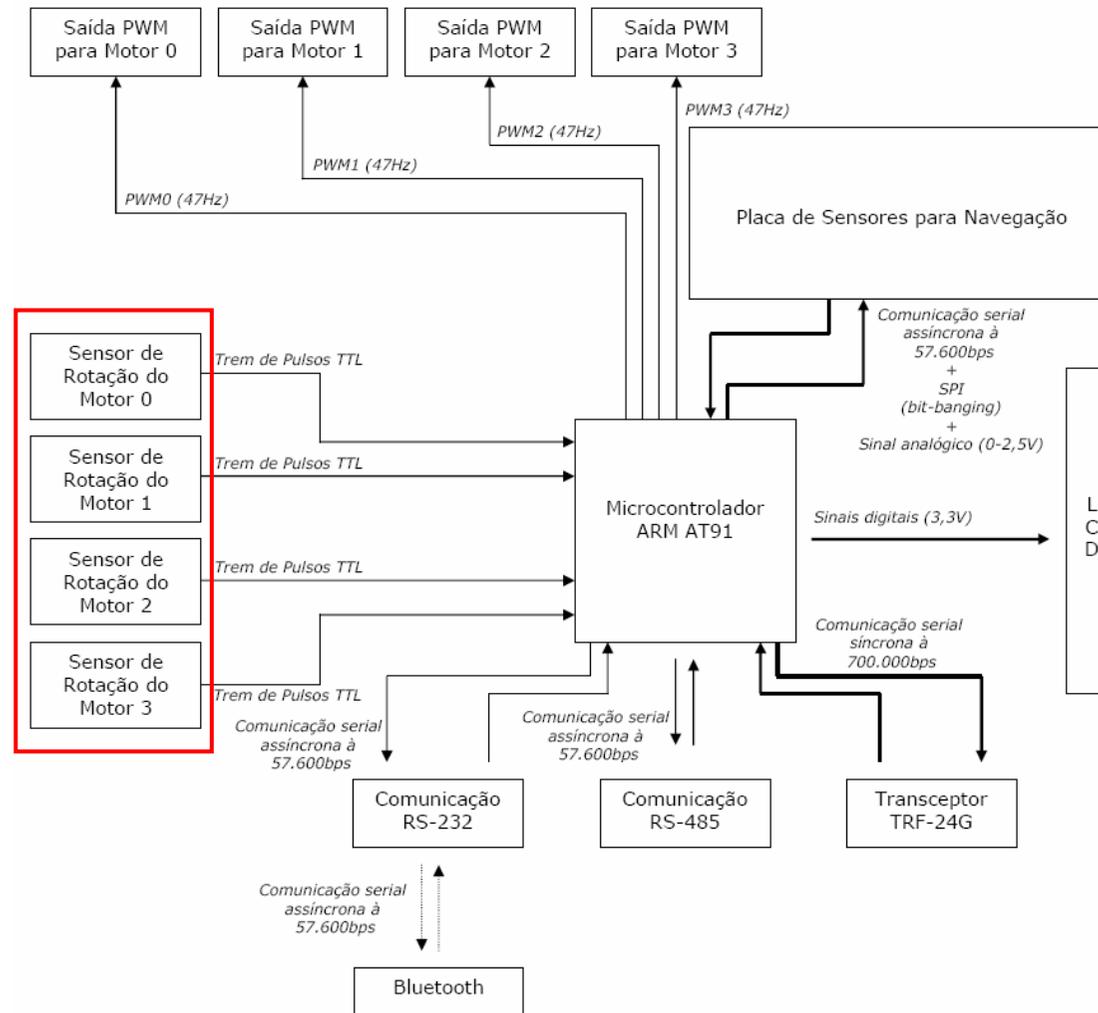
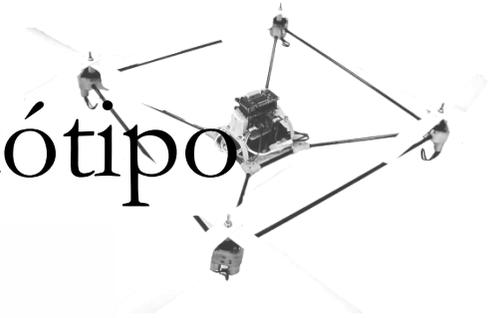
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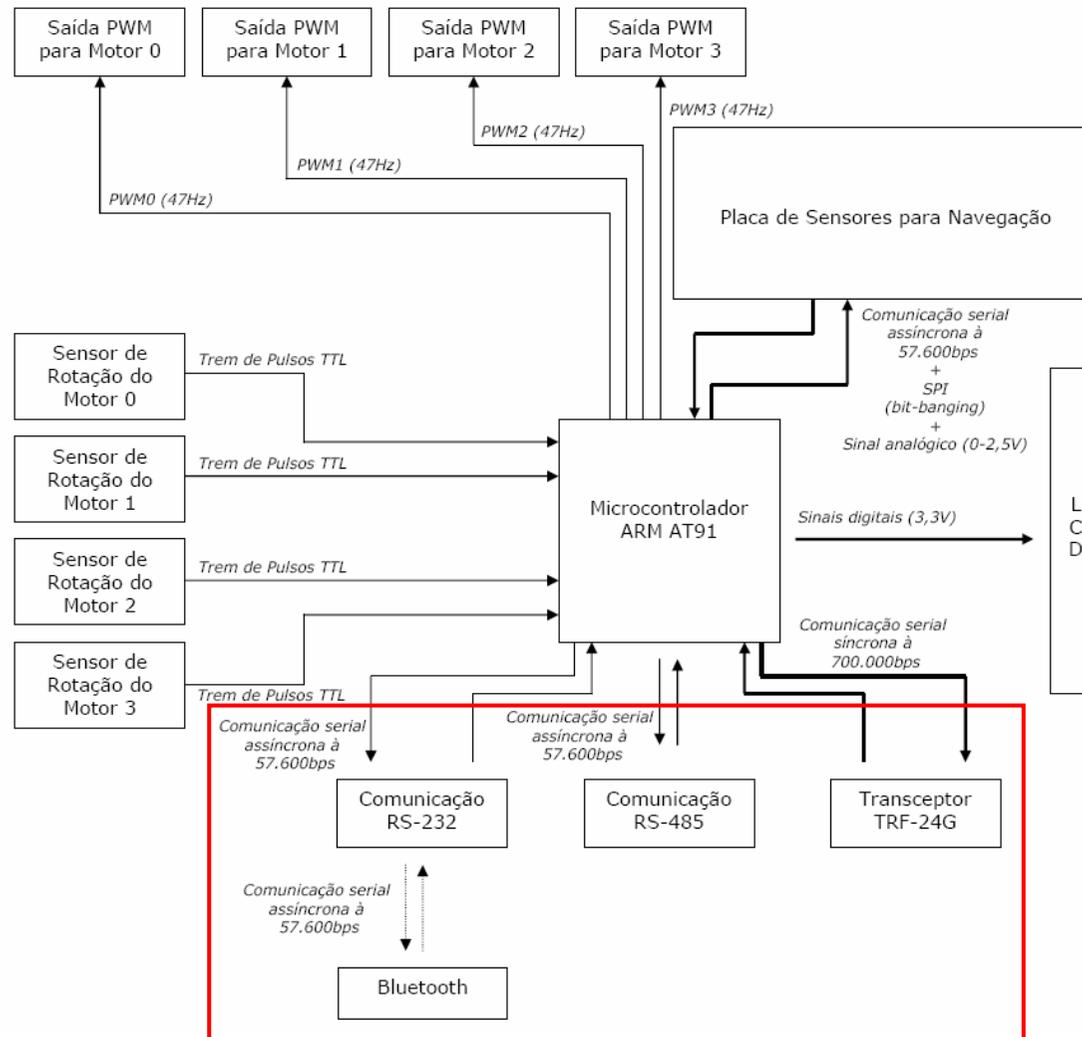
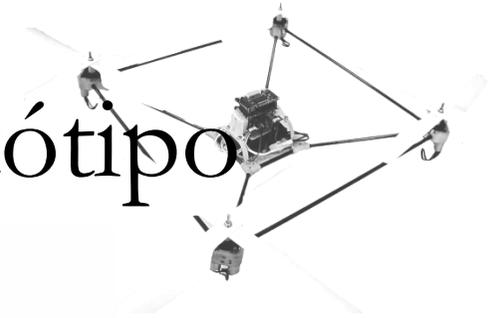
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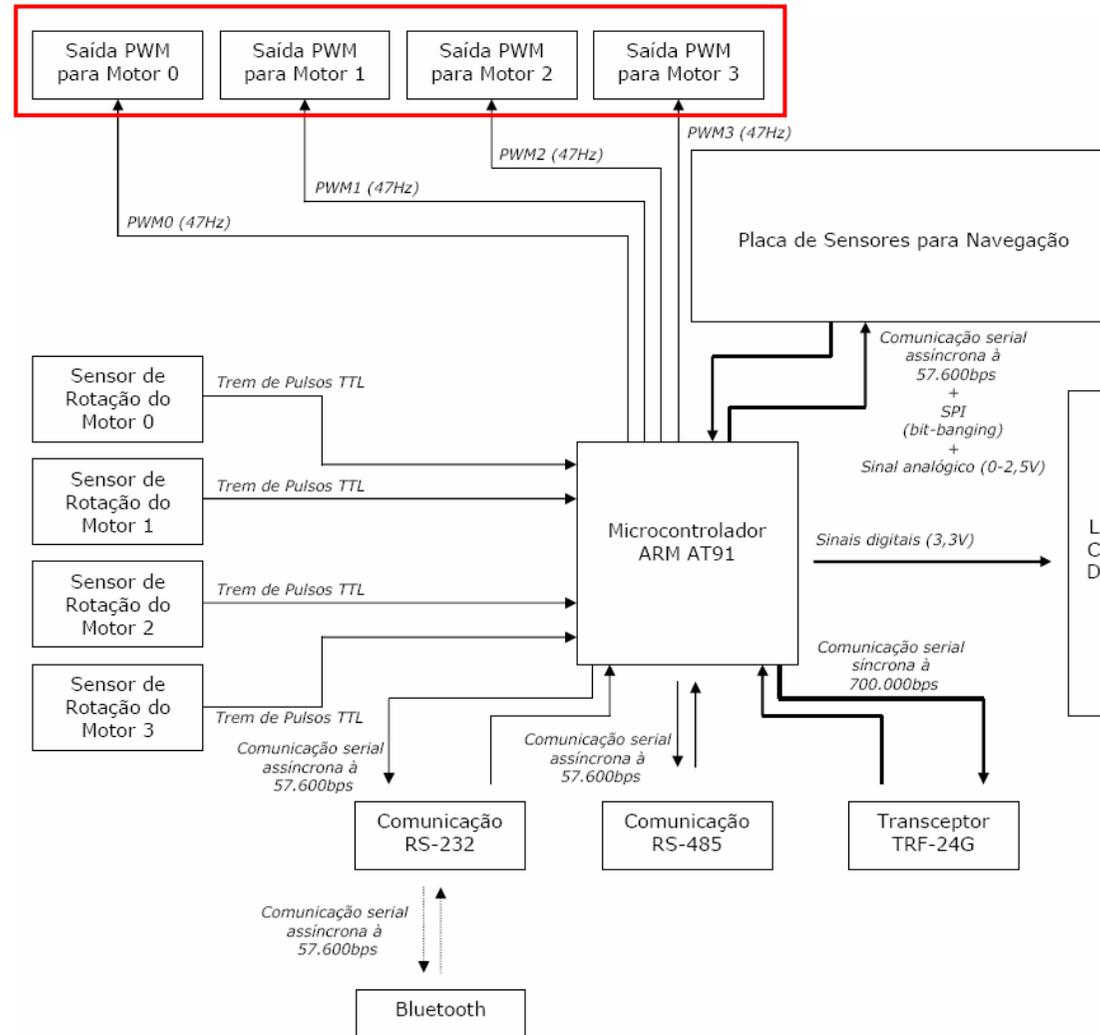
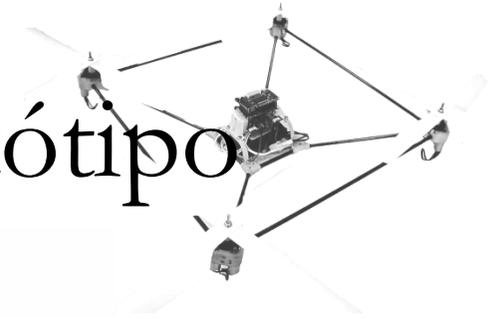
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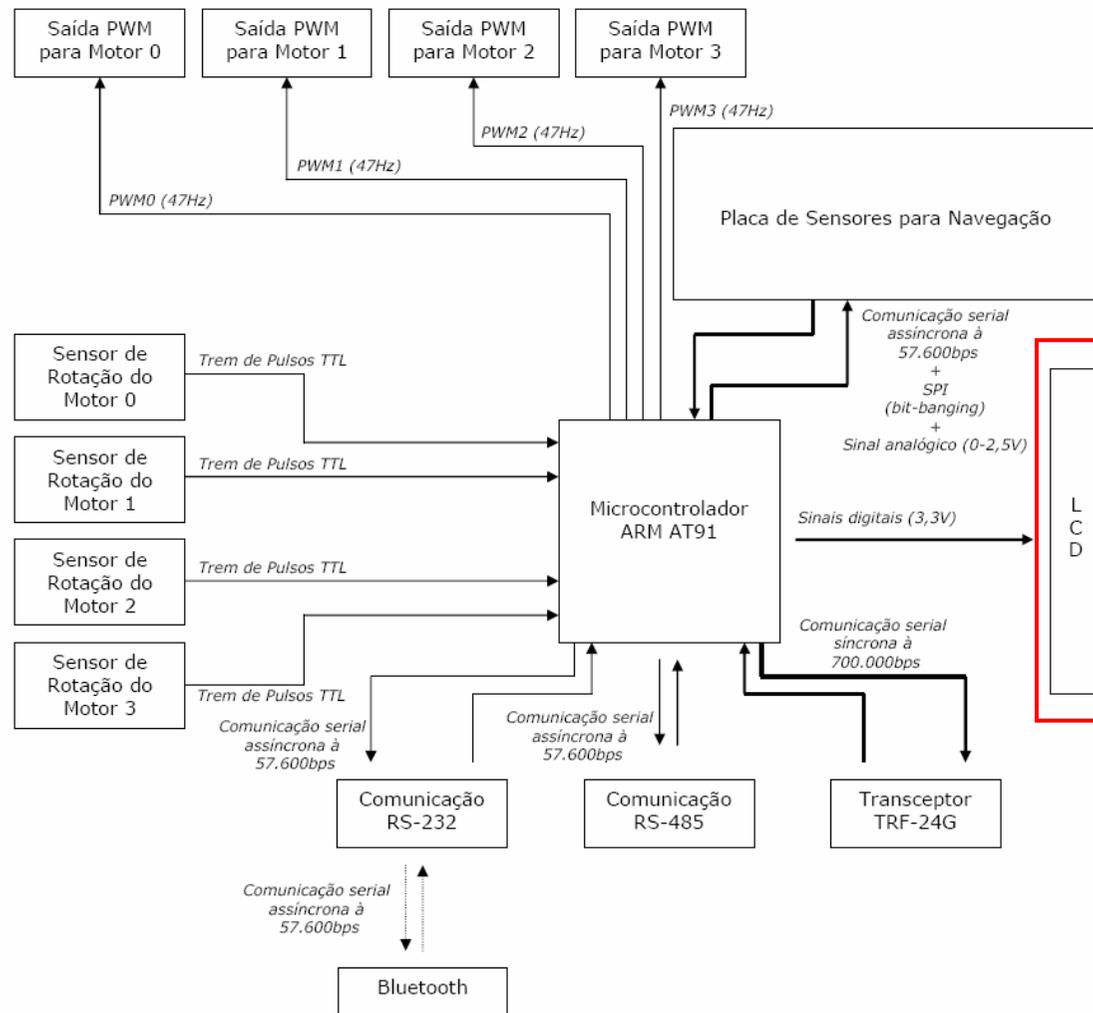
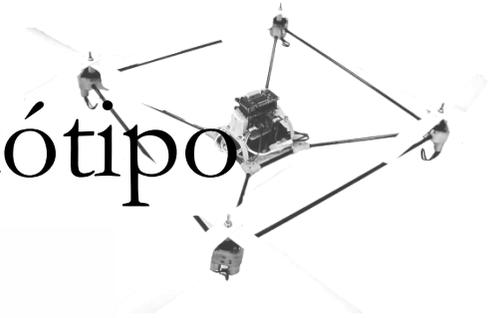
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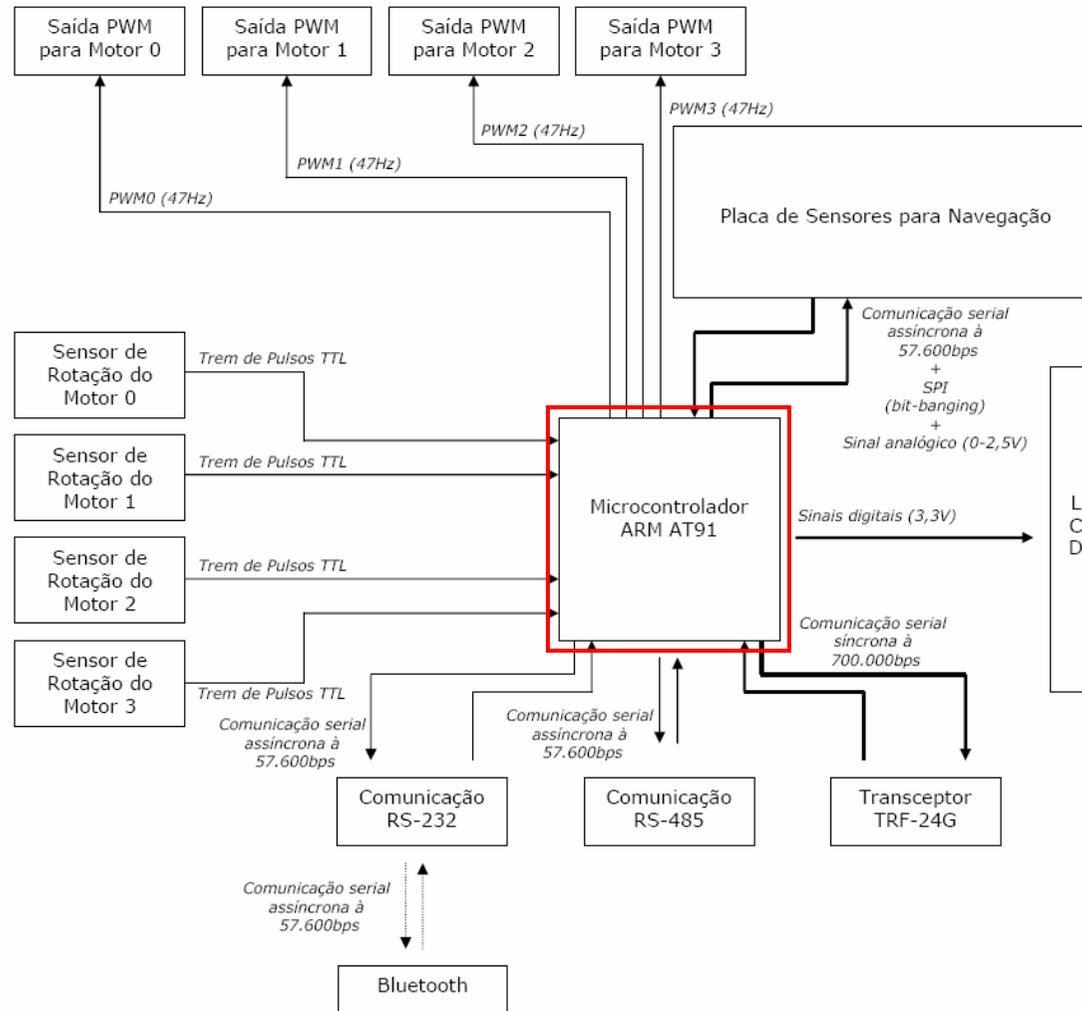
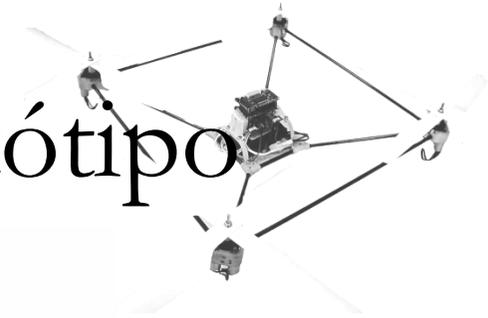
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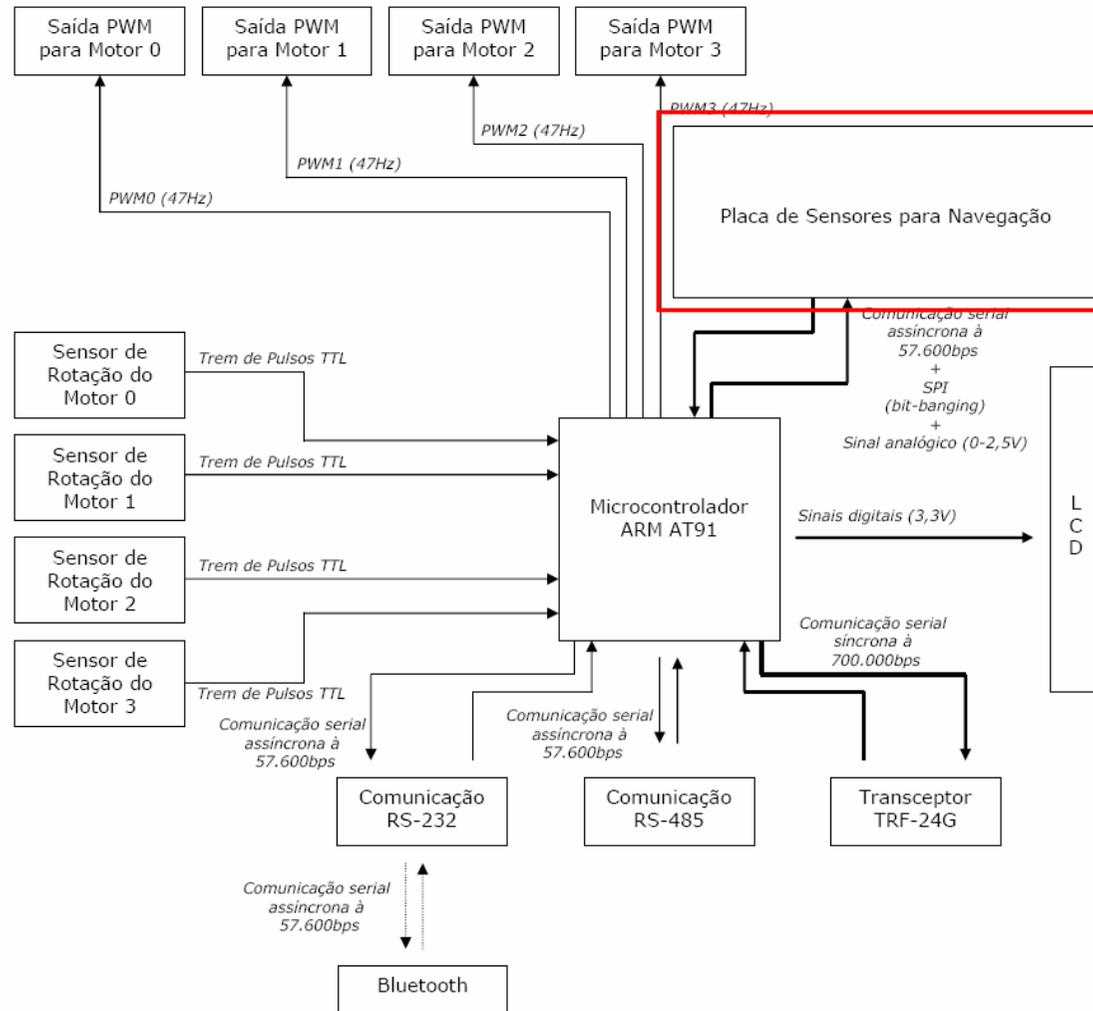
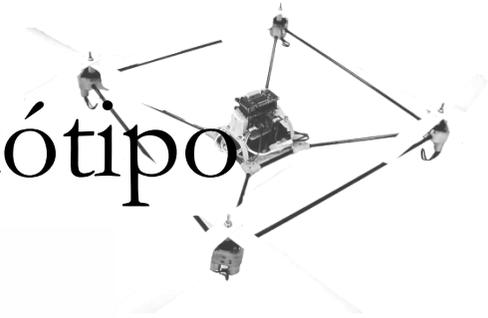
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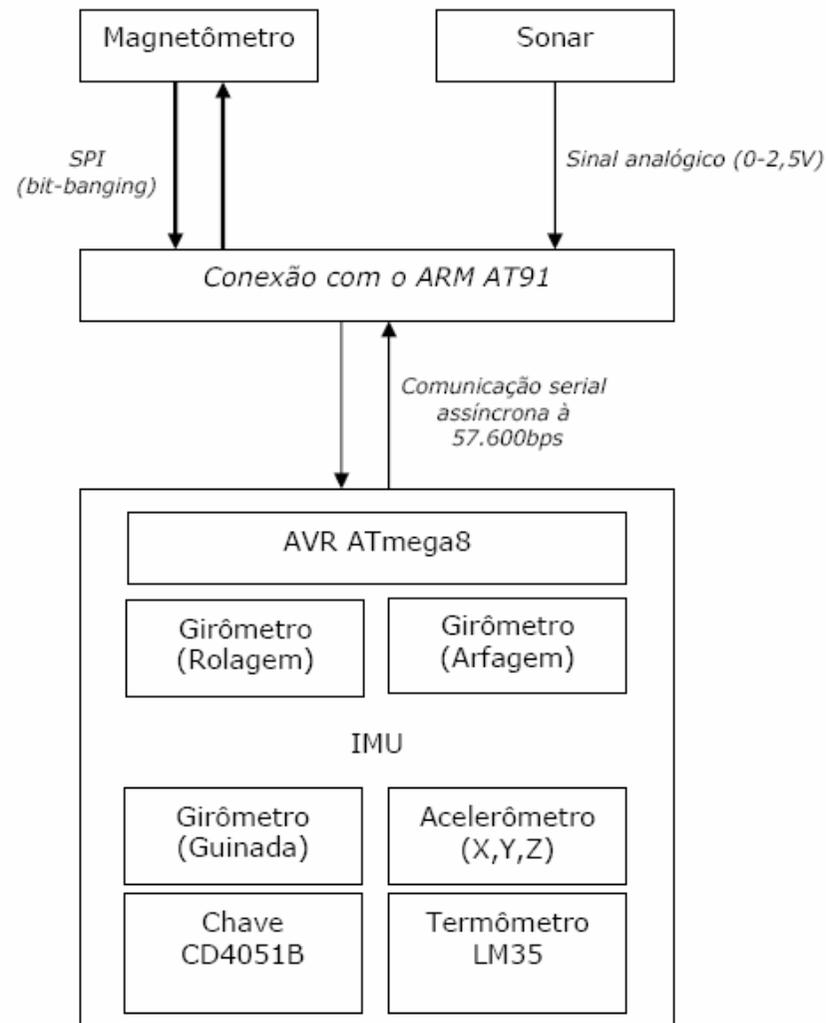
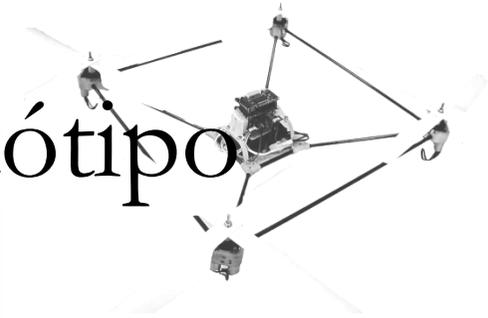
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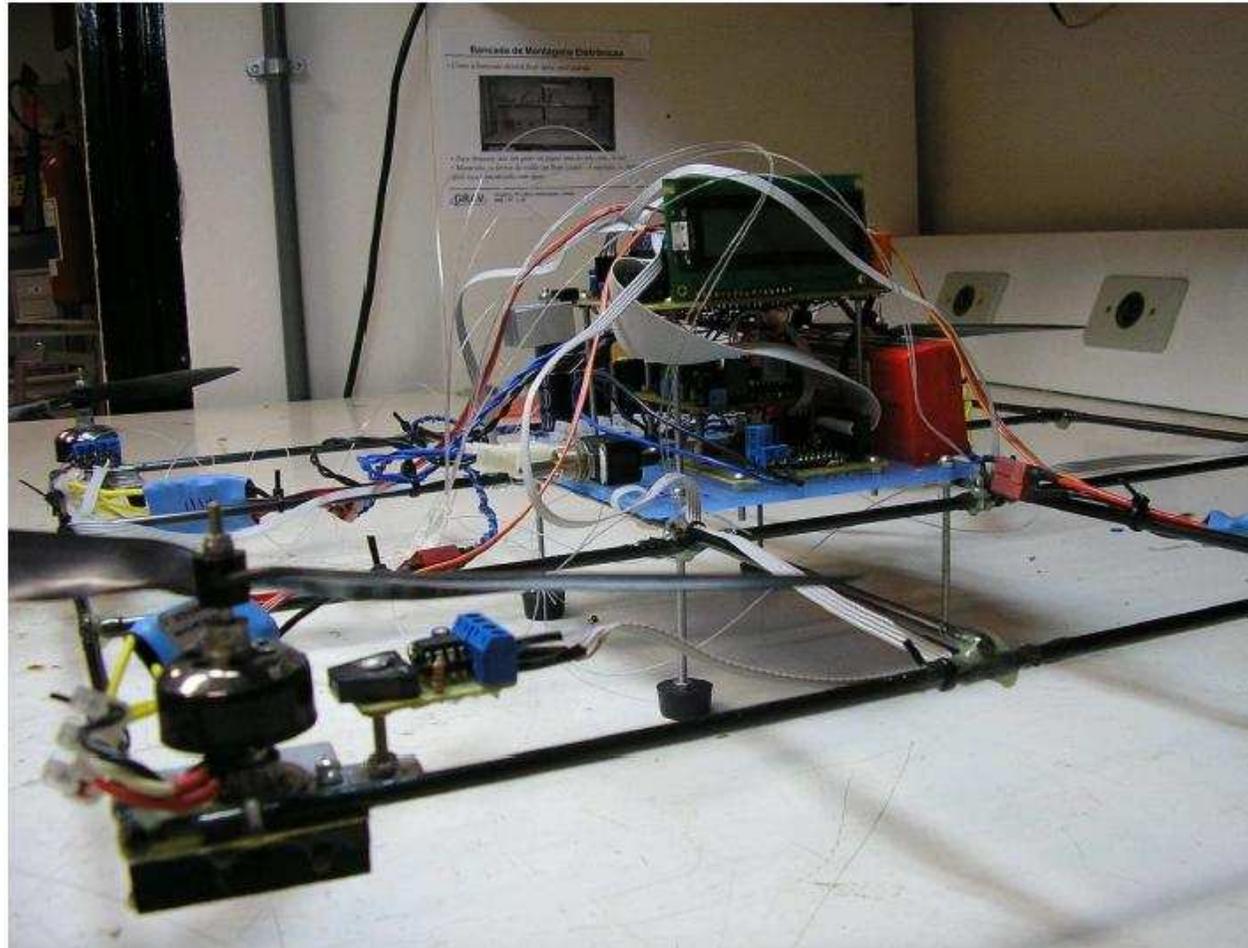
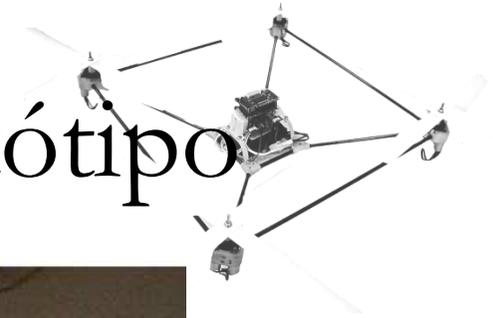
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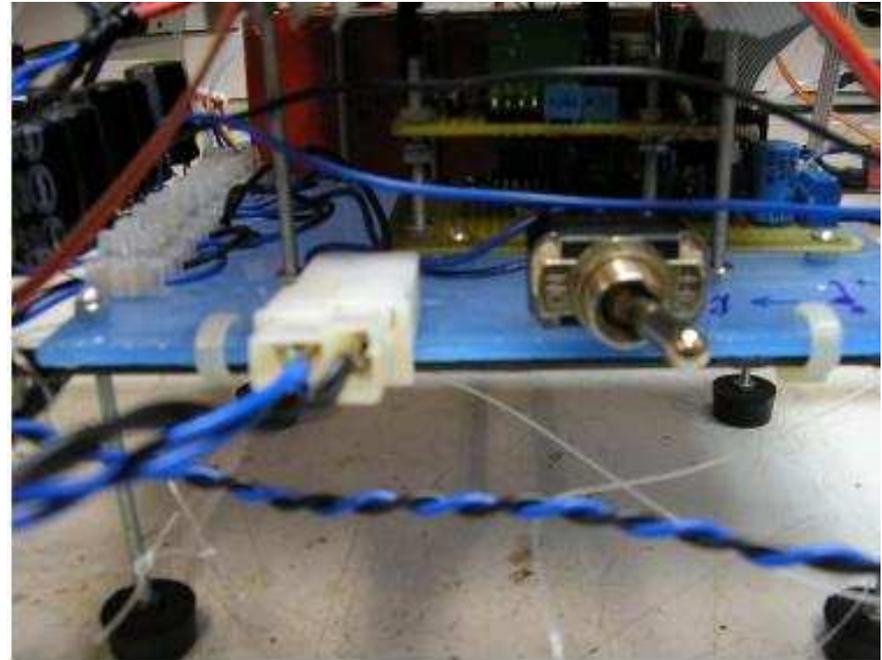
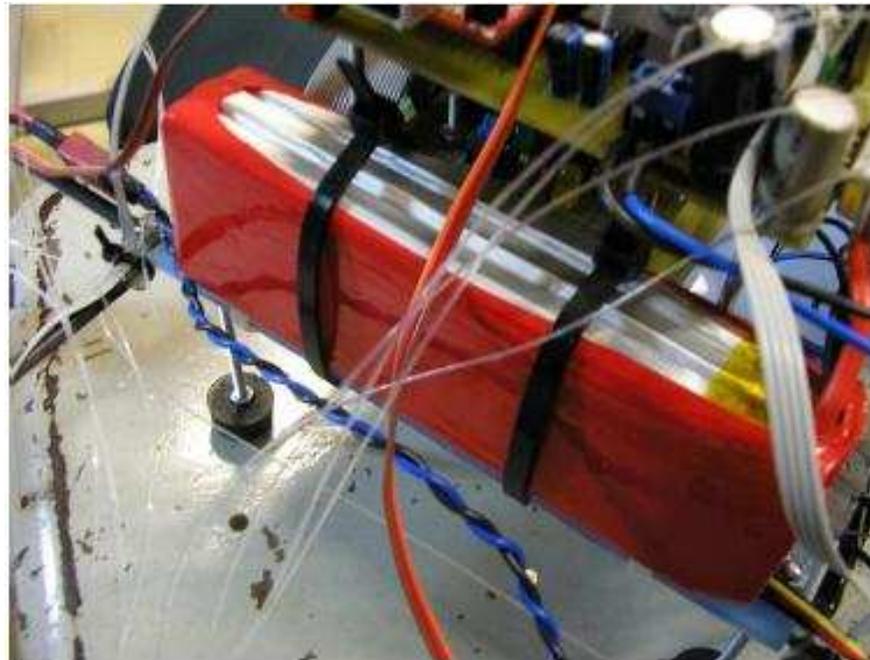
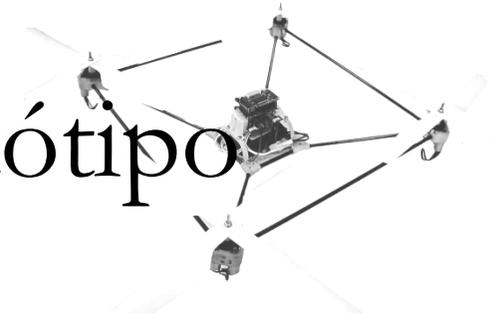
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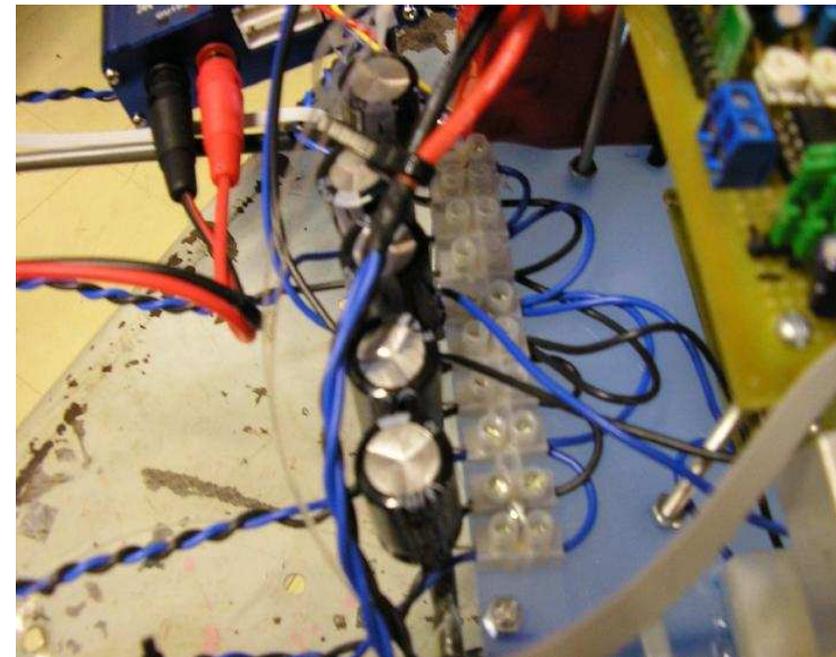
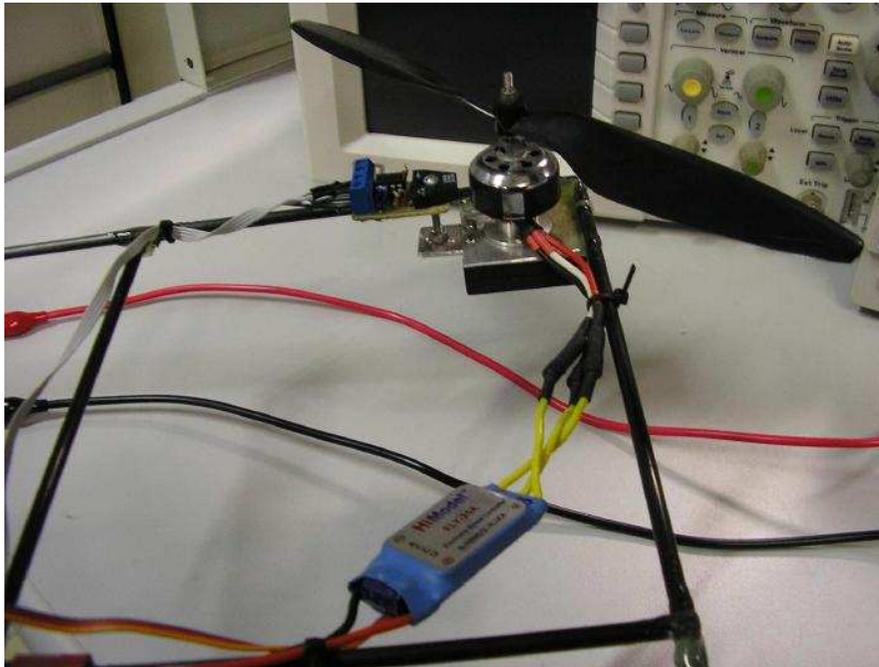
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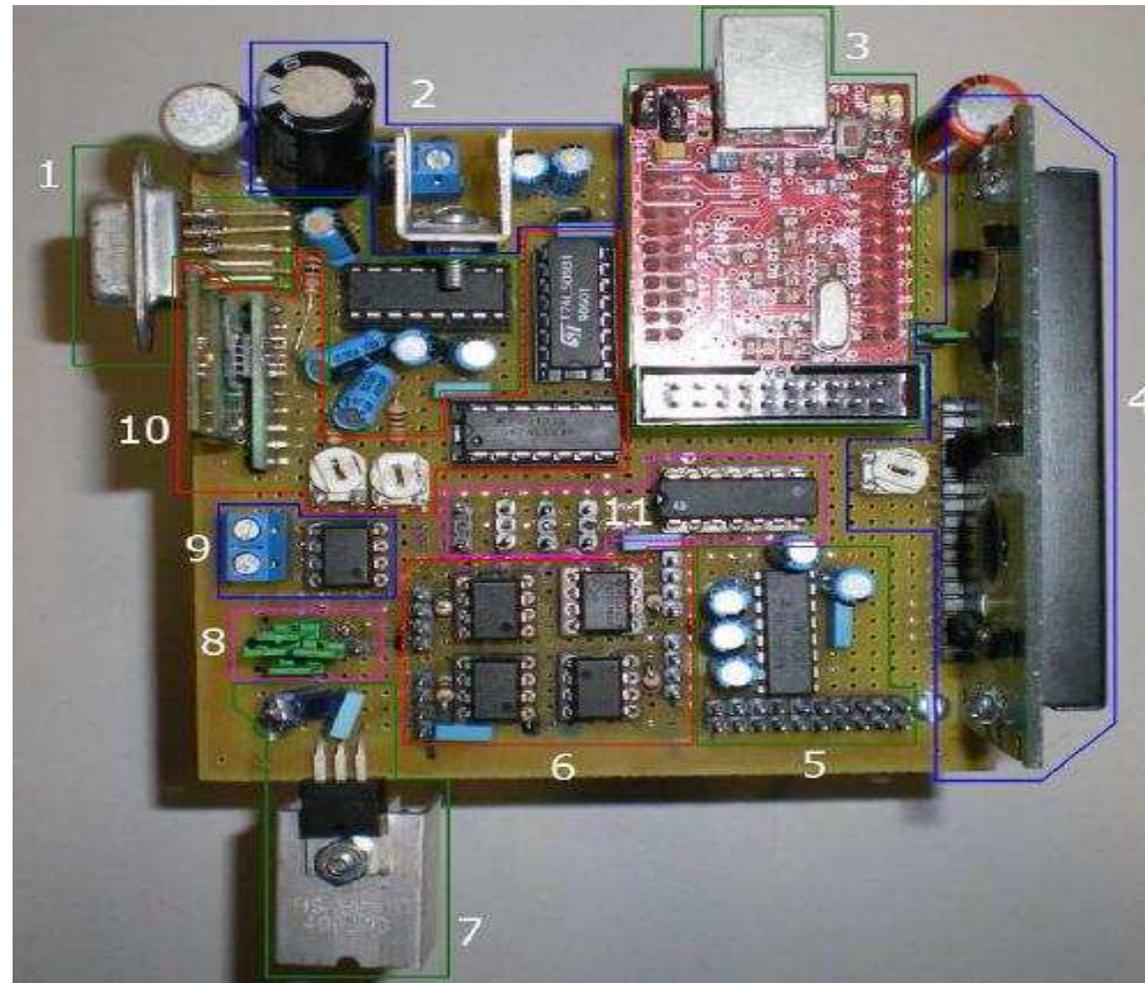
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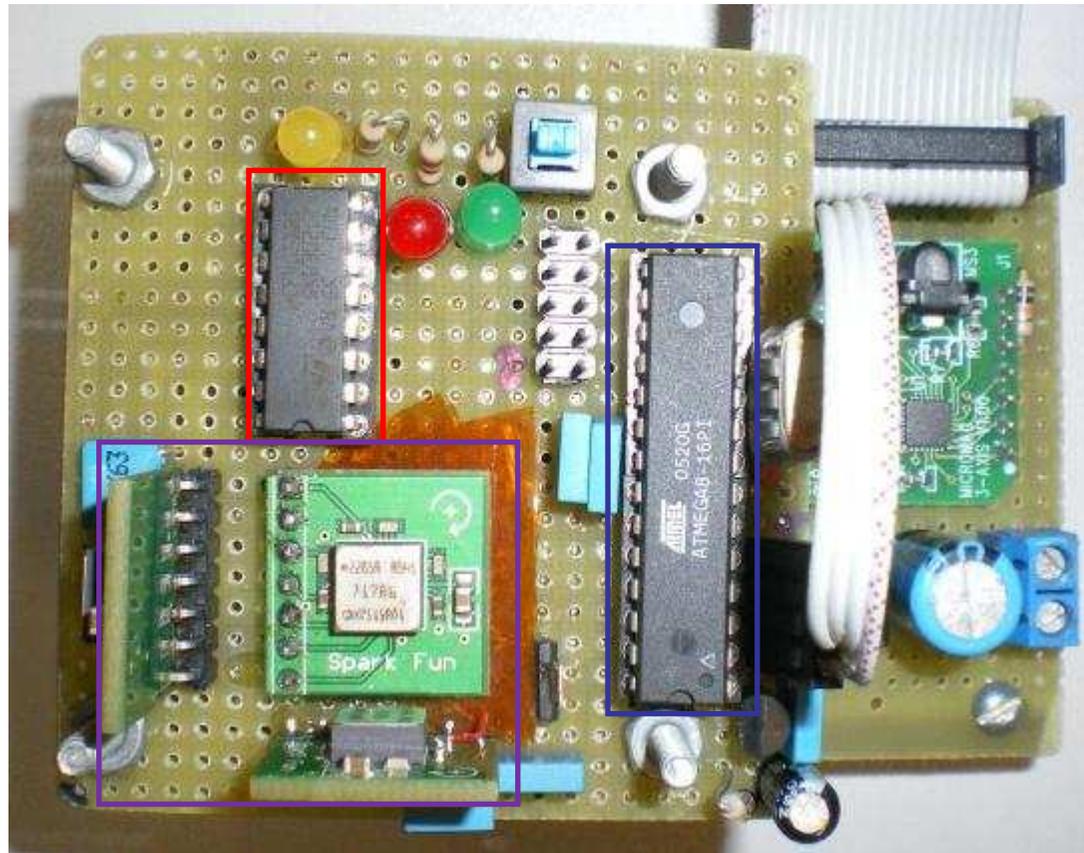
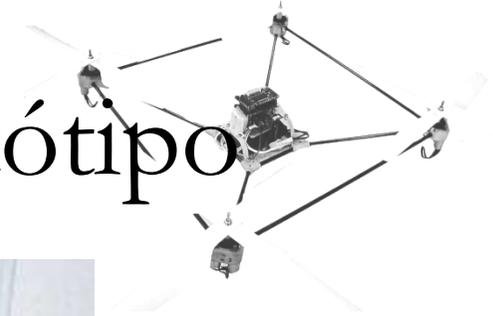
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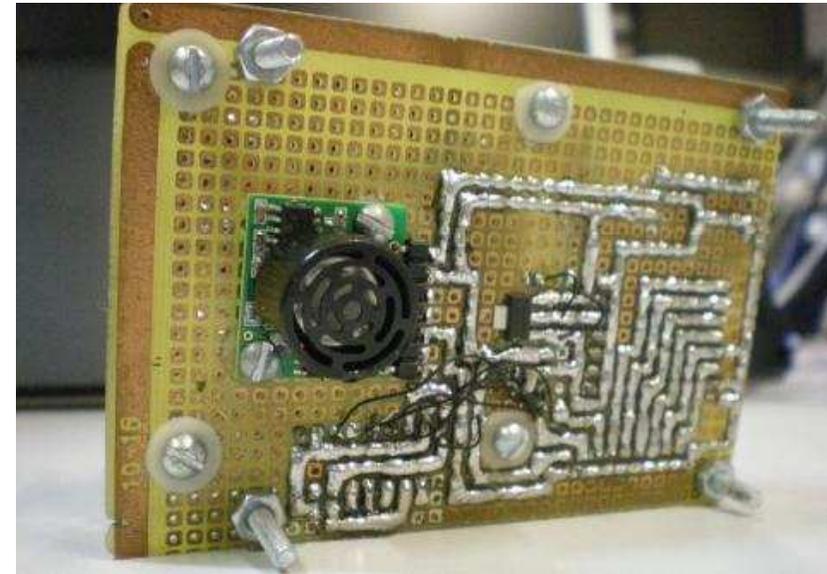
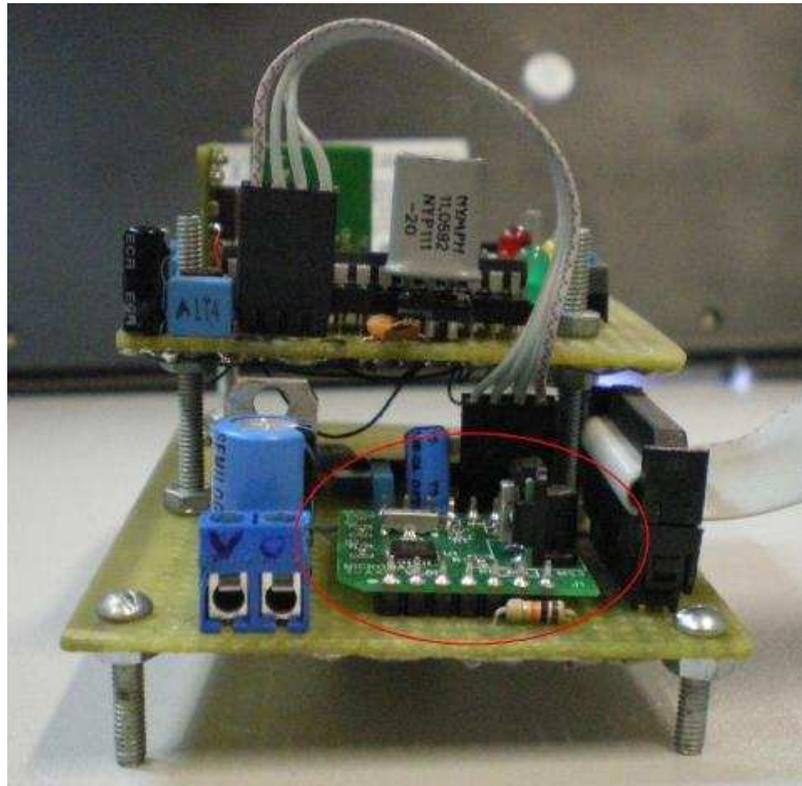
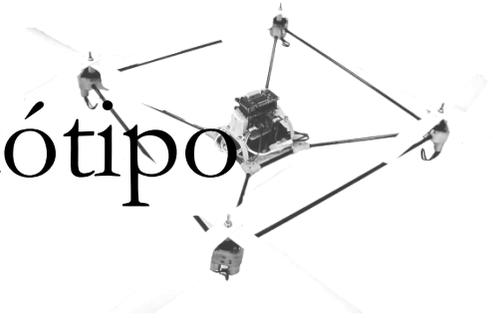
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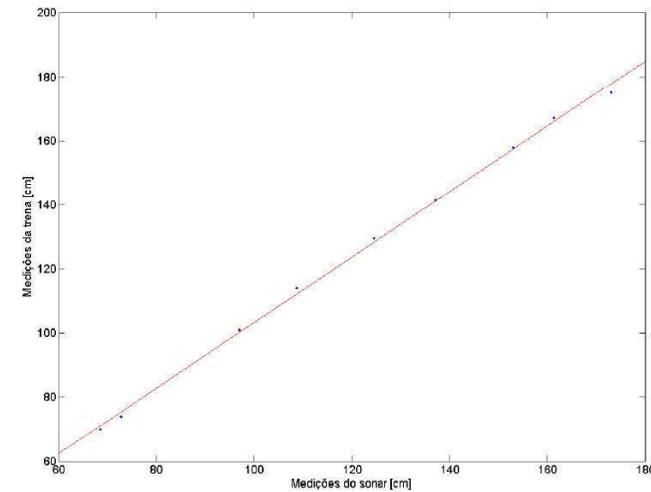
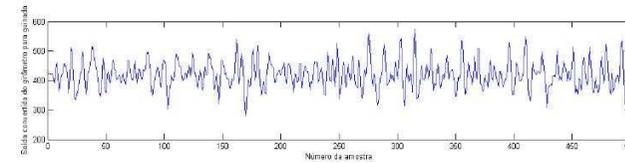
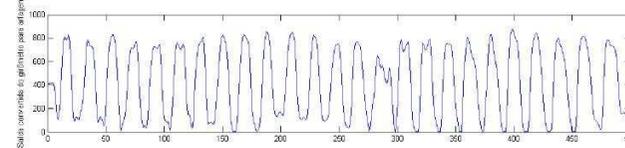
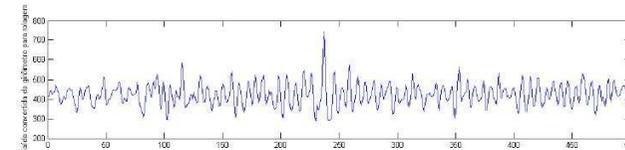
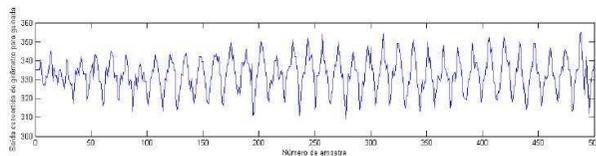
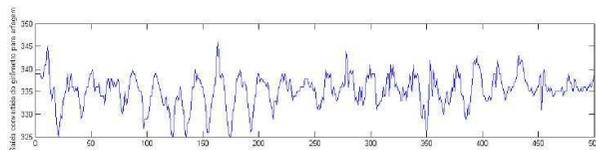
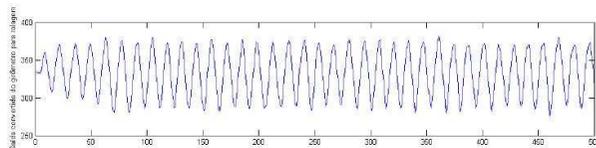
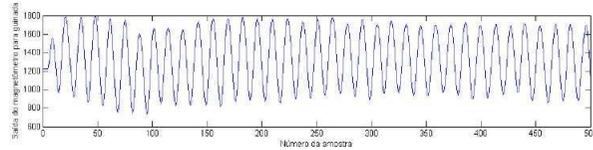
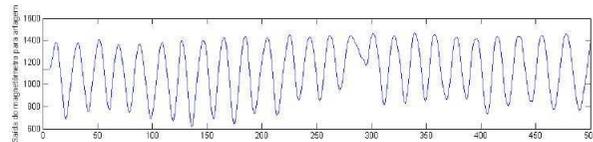
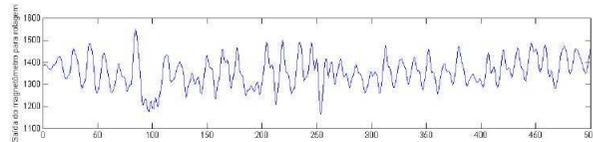
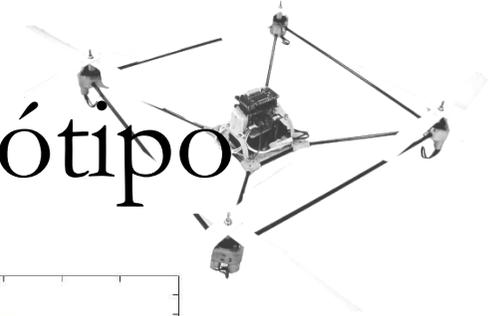
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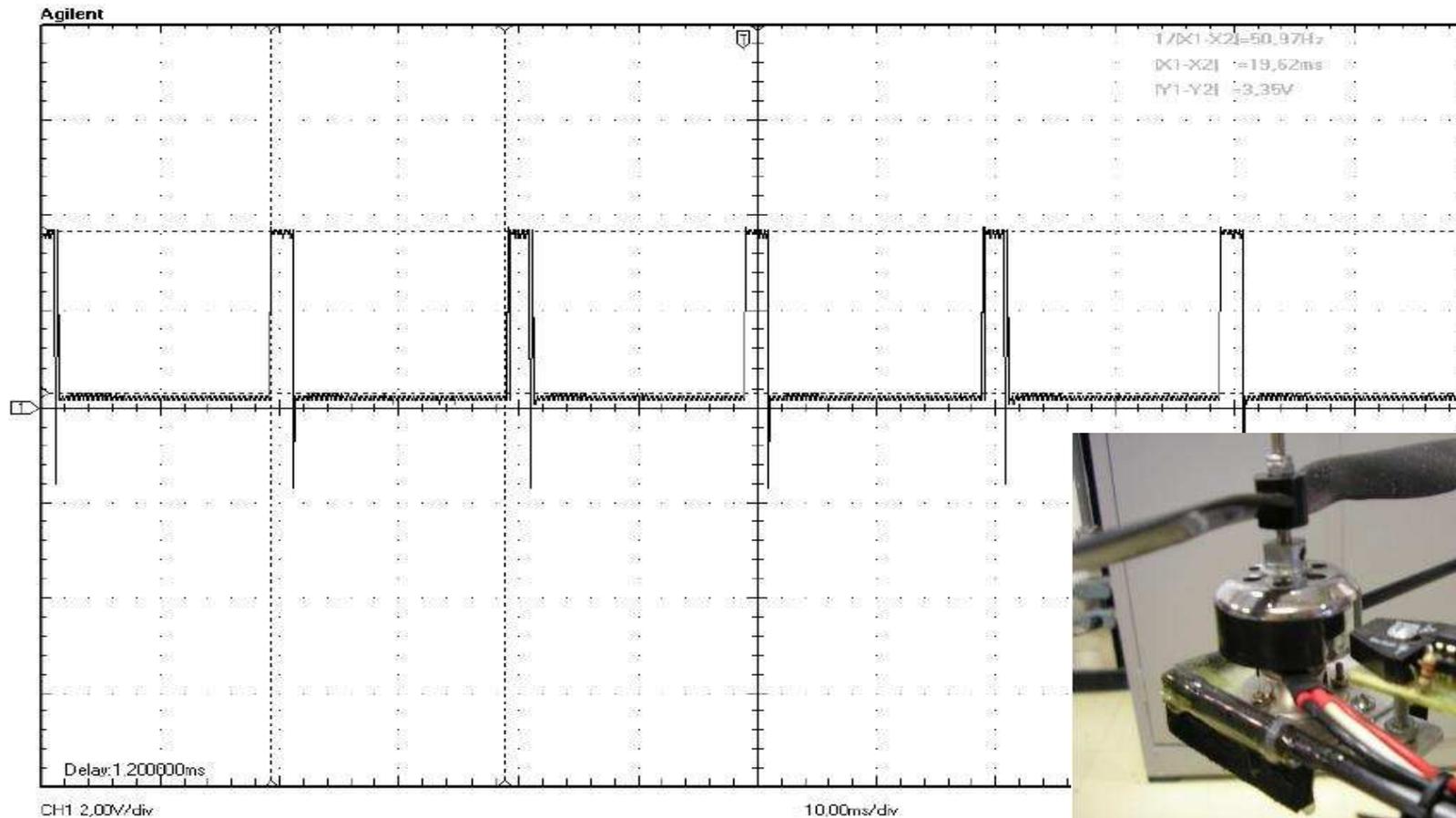
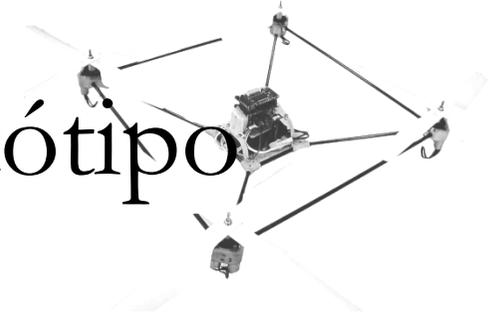
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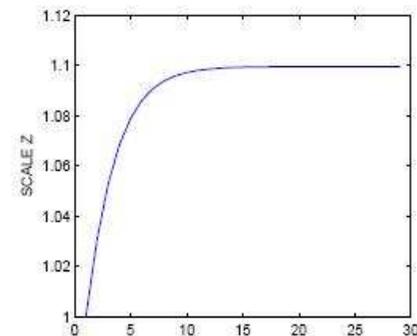
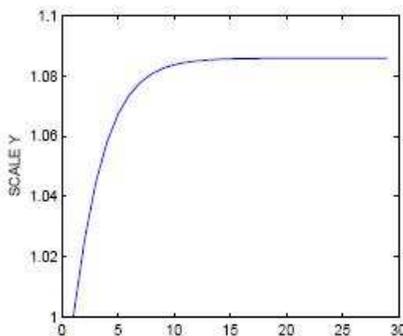
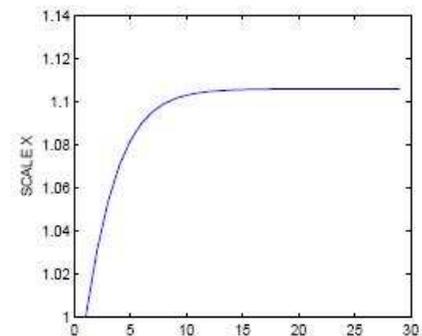
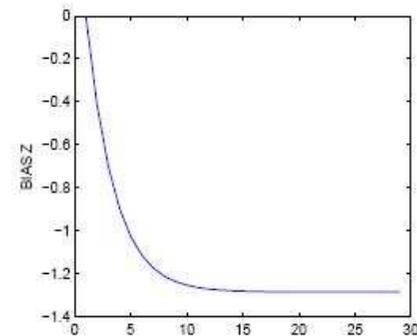
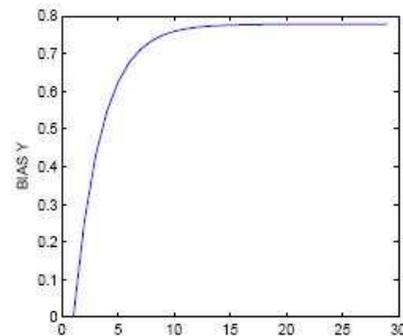
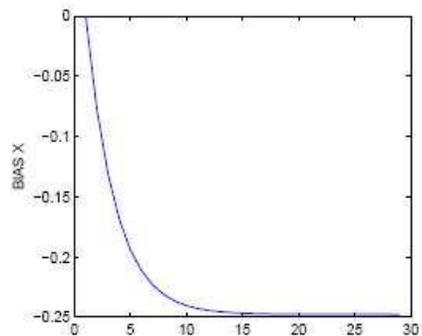
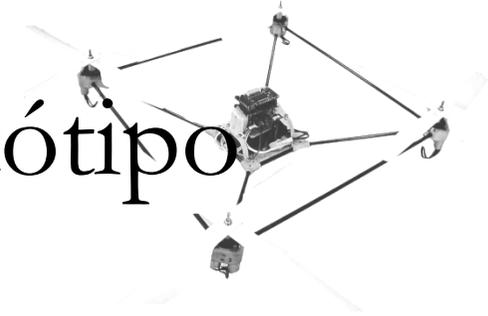
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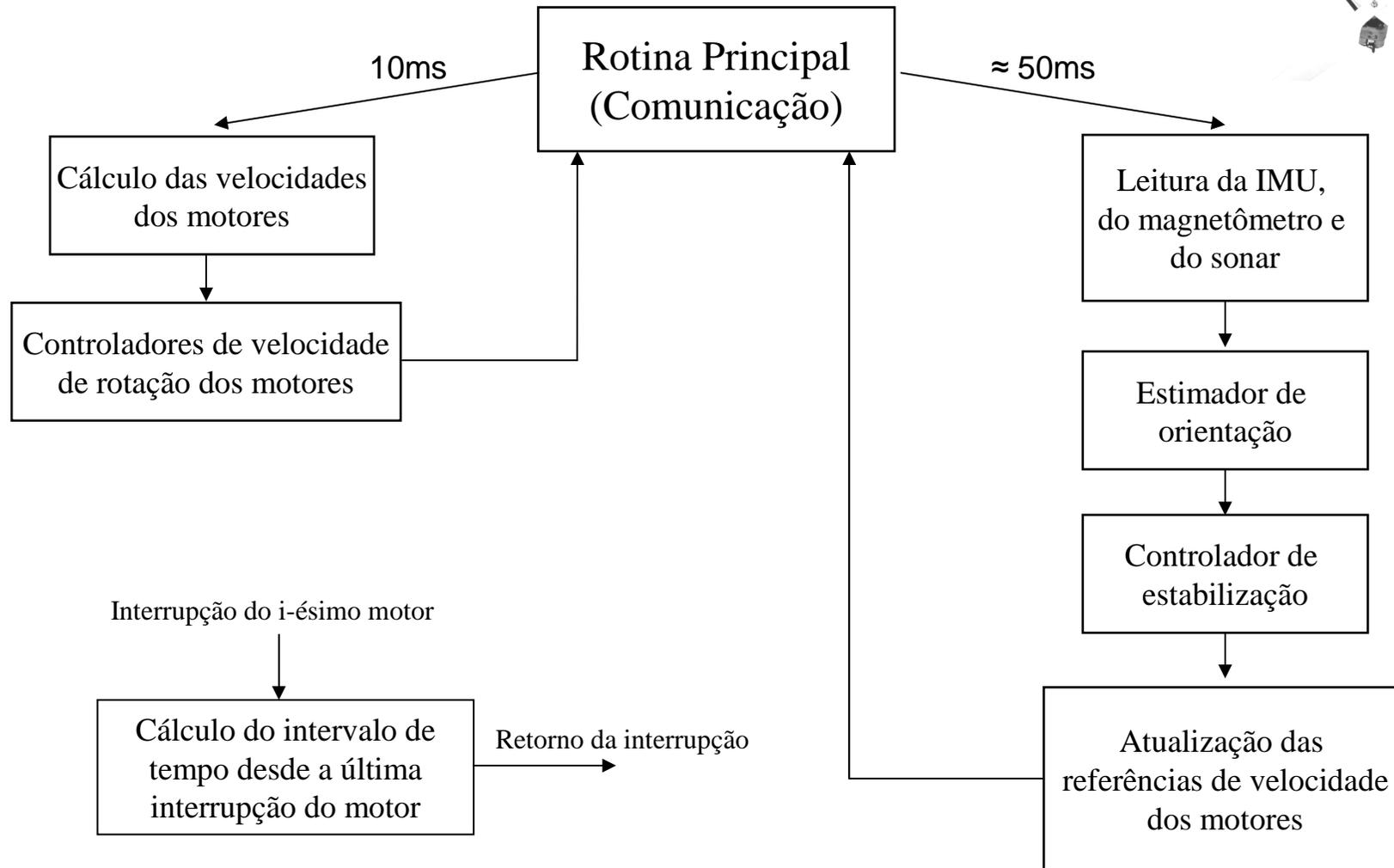
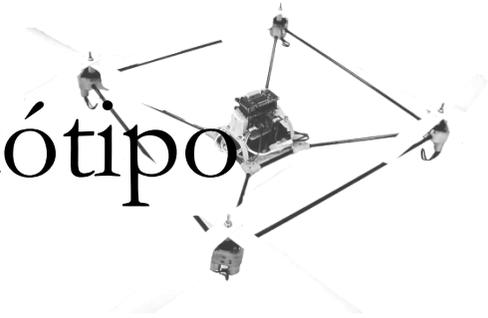
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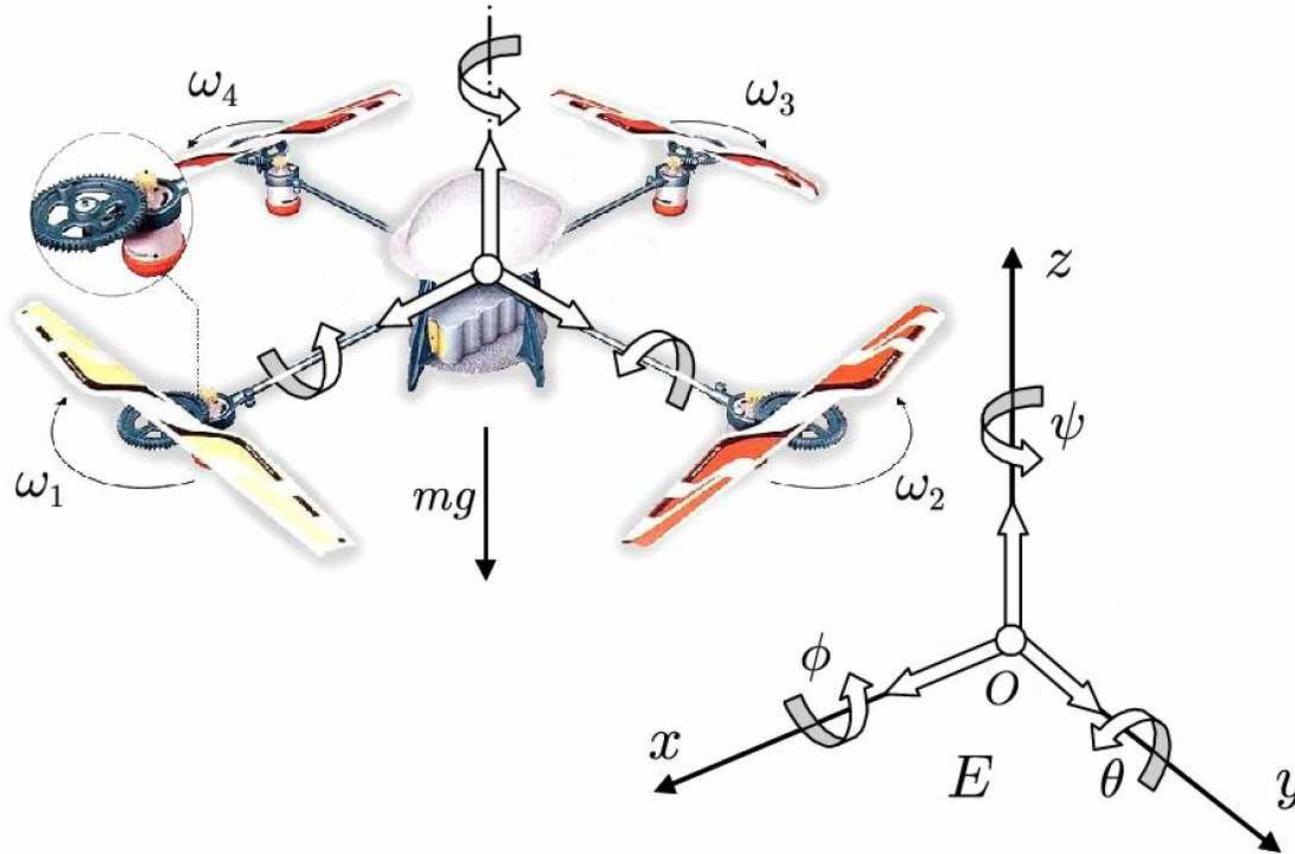
2. Desenvolvimento do protótipo



2. Desenvolvimento do protótipo



3. Modelamento matemático

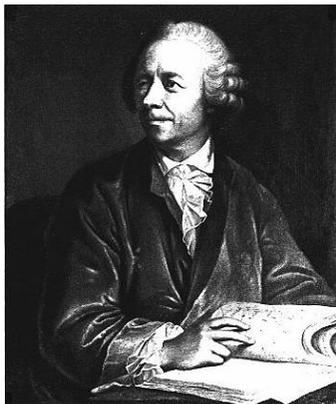


3. Modelamento matemático



Joseph-Louis de Lagrange

Isaac Newton



Leonhard Euler

X

Formalismo de Euler-Lagrange
(Lagrangiano)

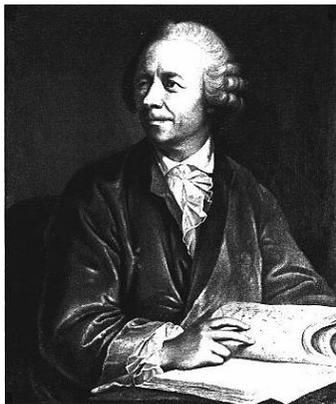
Leis de Newton

3. Modelamento matemático



Joseph-Louis de Lagrange

Isaac Newton



Leonhard Euler

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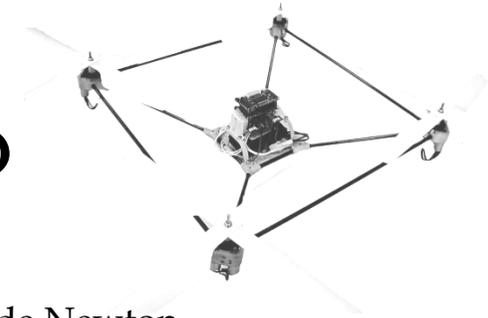
Formalismo de Euler-Lagrange
(Lagrangiano)

Dinâmica da rotação

Leis de Newton

Dinâmica da translação

3. Modelamento matemático

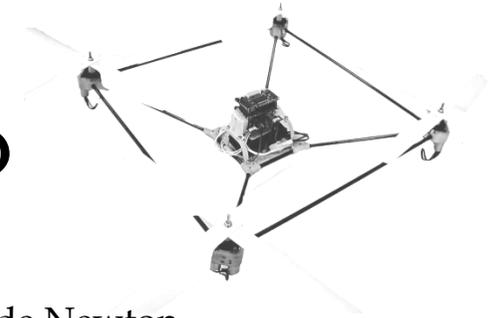


Lagrangiano

2ª Lei de Newton

$$\left\{ \begin{array}{l} L = T - V \\ \frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = \gamma_i \end{array} \right. \quad \sum \vec{F} = m \vec{a}$$

3. Modelamento matemático



Lagrangiano

2ª Lei de Newton

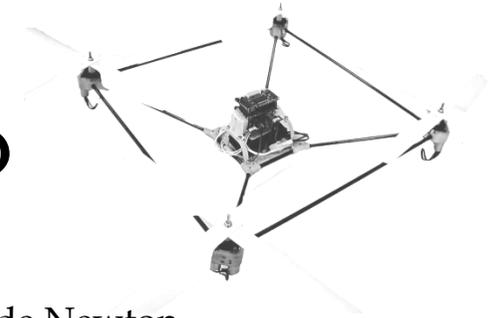
$$\left\{ \begin{array}{l} L = T - V \\ \frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = \gamma_i \end{array} \right. \quad \sum \vec{F} = m \vec{a}$$

$$\frac{d^2}{dt^2} x = (\cos(\psi) \sin(\theta) \cos(\phi) + \sin(\psi) \sin(\phi)) \times \frac{U}{m}$$

$$\frac{d^2}{dt^2} y = (\sin(\psi) \sin(\theta) \cos(\phi) - \sin(\phi) \cos(\psi)) \times \frac{U}{m}$$

$$\frac{d^2}{dt^2} z = -g + (\cos(\theta) \cos(\phi)) \times \frac{U}{m}$$

3. Modelamento matemático



Lagrangiano

2ª Lei de Newton

$$\left\{ \begin{array}{l} L = T - V \\ \frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = \gamma_i \end{array} \right. \quad \sum \vec{F} = m \vec{a}$$

Estas aqui merecem um pouco mais de detalhes...

$$\frac{d^2}{dt^2}x = (\cos(\psi) \sin(\theta) \cos(\phi) + \sin(\psi) \sin(\phi)) \times \frac{U}{m}$$

$$\frac{d^2}{dt^2}y = (\sin(\psi) \sin(\theta) \cos(\phi) - \sin(\phi) \cos(\psi)) \times \frac{U}{m}$$

$$\frac{d^2}{dt^2}z = -g + (\cos(\theta) \cos(\phi)) \times \frac{U}{m}$$

3. Modelamento matemático



$$\frac{d^2\phi}{dt^2} = \frac{d^2\psi}{dt^2} \sin(\theta) + \frac{\frac{d\psi}{dt} \frac{d\theta}{dt} \cos(\theta) (I_{xx} + (I_{yy} - I_{zz})(2 \cos(\phi)^2 - 1))}{I_{xx}} - \frac{1}{2} \frac{d\theta^2}{dt} \sin(2\phi) \frac{I_{yy} - I_{zz}}{I_{xx}} + \frac{1}{2} \frac{d\psi^2}{dt} \sin(2\phi) \cos(\theta)^2 \frac{I_{yy} - I_{zz}}{I_{xx}} + \frac{\tau_x}{I_{xx}}$$

$$\frac{d^2\theta}{dt^2} = \frac{-\frac{d^2\psi}{dt^2} (1/2) \sin(2\phi) \cos(\theta) (I_{yy} - I_{zz})}{I_{yy} \cos(\phi)^2 + I_{zz} \sin(\phi)^2} - \frac{\frac{1}{2} \frac{d\psi^2}{dt} \sin(2\theta) (-I_{xx} + I_{yy} \sin(\phi)^2 + I_{zz} \cos(\phi)^2)}{I_{yy} \cos(\phi)^2 + I_{zz} \sin(\phi)^2} + \frac{\frac{d\theta}{dt} \frac{d\phi}{dt} \sin(2\phi) (I_{zz} - I_{yy})}{I_{yy} \cos(\phi)^2 + I_{zz} \sin(\phi)^2} + \frac{\frac{d\psi}{dt} \frac{d\phi}{dt} \cos(\theta) (\cos(2\phi) (I_{yy} - I_{zz}) + I_{xx}) + \tau_y}{I_{yy} \cos(\phi)^2 + I_{zz} \sin(\phi)^2}$$

Assumindo que os ângulos de inclinação são pequenos

$$\frac{d^2\phi}{dt^2} = \frac{I_{yy} - I_{zz}}{I_{xx}} \frac{d\psi}{dt} \frac{d\theta}{dt} + \frac{\tau_x}{I_{xx}}$$

$$\frac{d^2\theta}{dt^2} = \frac{I_{zz} - I_{xx}}{I_{yy}} \frac{d\psi}{dt} \frac{d\phi}{dt} + \frac{\tau_y}{I_{yy}}$$

$$\frac{d^2\psi}{dt^2} = \frac{\frac{d^2\phi}{dt^2} \sin(\theta) I_{xx} - \frac{d^2\theta}{dt^2} \frac{1}{2} \sin(2\phi) \cos(\theta) (I_{yy} - I_{zz})}{\cos(\theta)^2 (I_{zz} \cos(\phi)^2 + I_{yy} \sin(\phi)^2) + \sin(\theta)^2 I_{xx}} - \frac{\frac{d\theta}{dt} \frac{d\psi}{dt} \sin(2\theta) (I_{xx} - I_{zz} \cos(\phi)^2 + I_{yy} \sin(\phi)^2)}{\cos(\theta)^2 (I_{zz} \cos(\phi)^2 + I_{yy} \sin(\phi)^2) + \sin(\theta)^2 I_{xx}} - \frac{\frac{d\theta}{dt} \frac{d\psi}{dt} \sin(2\theta) (I_{xx} - I_{zz} \cos(\phi)^2 + I_{yy} \sin(\phi)^2)}{\cos(\theta)^2 (I_{zz} \cos(\phi)^2 + I_{yy} \sin(\phi)^2) + \sin(\theta)^2 I_{xx}} + \frac{\frac{d\psi}{dt} \frac{d\phi}{dt} \sin(2\phi) \cos(\theta)^2 (I_{yy} - I_{zz})}{\cos(\theta)^2 (I_{zz} \cos(\phi)^2 + I_{yy} \sin(\phi)^2) + \sin(\theta)^2 I_{xx}} - \frac{\frac{d\theta}{dt} \frac{d\phi}{dt} \cos(\theta) (I_{xx} + (2 \cos(\phi)^2 - 1) (I_{yy} - I_{zz}))}{\cos(\theta)^2 (I_{zz} \cos(\phi)^2 + I_{yy} \sin(\phi)^2) + \sin(\theta)^2 I_{xx}} + \frac{\frac{1}{2} \frac{d\theta^2}{dt} \sin(2\phi) \sin(\theta) (I_{yy} - I_{zz}) + \tau_z}{\cos(\theta)^2 (I_{zz} \cos(\phi)^2 + I_{yy} \sin(\phi)^2) + \sin(\theta)^2 I_{xx}}$$

$$\frac{d^2\psi}{dt^2} = \frac{I_{xx} - I_{yy}}{I_{zz}} \frac{d\theta}{dt} \frac{d\phi}{dt} + \frac{\tau_z}{I_{zz}}$$

3. Modelamento matemático



Alguém deve estar se perguntando agora:

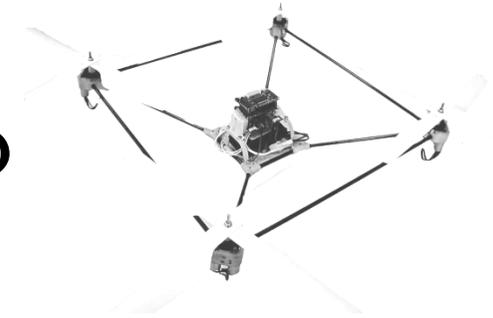
3. Modelamento matemático



Alguém deve estar se perguntando agora:

QUAL FOI O PROPÓSITO DE TODAS ESTAS EQUAÇÕES?!

3. Modelamento matemático



Alguém deve estar se perguntando agora:

QUAL FOI O PROPÓSITO DE TODAS ESTAS EQUAÇÕES?!

- Em suma, foram dois:
 - Conceber um simulador da dinâmica do quadrirrotor;
 - Desenvolver o controle de estabilização.

4. Localização

- Ângulos de Euler

$$R(x, \phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & -\text{sen}(\phi) \\ 0 & \text{sen}(\phi) & \cos(\phi) \end{bmatrix}$$

$$R(y, \theta) = \begin{bmatrix} \cos(\theta) & 0 & \text{sen}(\theta) \\ 0 & 1 & 0 \\ -\text{sen}(\theta) & 0 & \cos(\theta) \end{bmatrix}$$

$$R(z, \psi) = \begin{bmatrix} \cos(\psi) & -\text{sen}(\psi) & 0 \\ \text{sen}(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



4. Localização

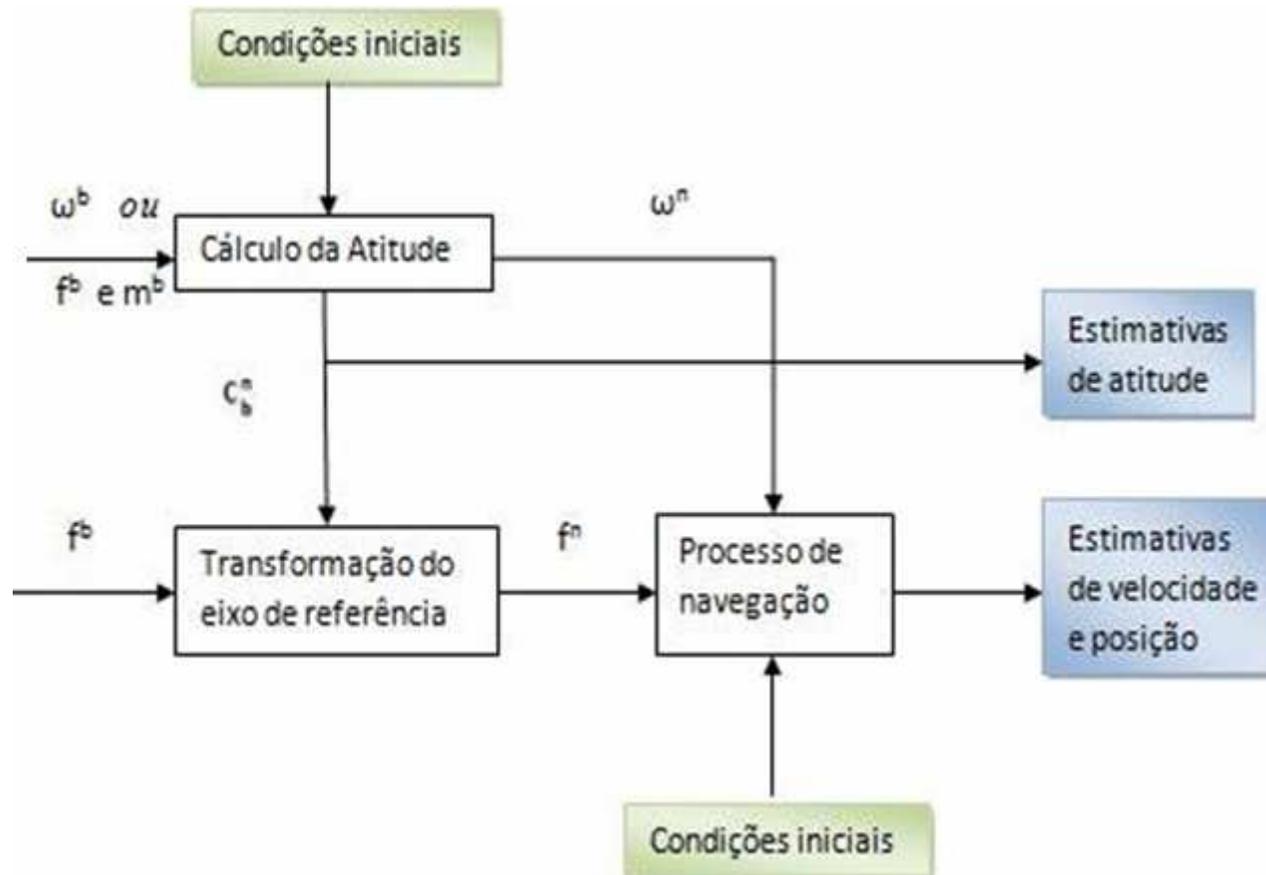
- Quatérnio



$$\mathbf{q} = q_0 + q_1\mathbf{i} + q_2\mathbf{j} + q_3\mathbf{k}$$

$$\mathbf{q}_f^m = \mathbf{q}_f^{m(N)} = \mathbf{q}_f^{m(0)} \otimes \dots \otimes \mathbf{q}_{m(N-2)}^{m(N-1)} \otimes \mathbf{q}_{m(N-1)}^{m(N)}$$

4. Localização



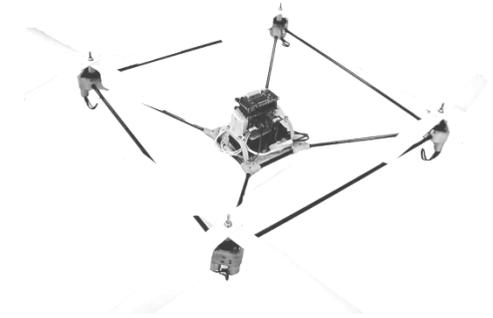
4. Localização

- Método TRIAD melhorado

$$M_r = [I_r : J_r : K_r]$$

$$M_b = [I_b : J_b : K_b]$$

$$C_{obs}^{ref} = M_b M_r^T$$



- Método utilizando os girômetros

$$\dot{\mathbf{q}} = -\frac{1}{2} \begin{bmatrix} 0 & \omega_x & \omega_y & \omega_z \\ -\omega_x & 0 & -\omega_z & \omega_y \\ -\omega_y & \omega_z & 0 & -\omega_x \\ -\omega_z & -\omega_y & \omega_x & 0 \end{bmatrix} \mathbf{q}$$

4. Localização

- Velocidade e posição

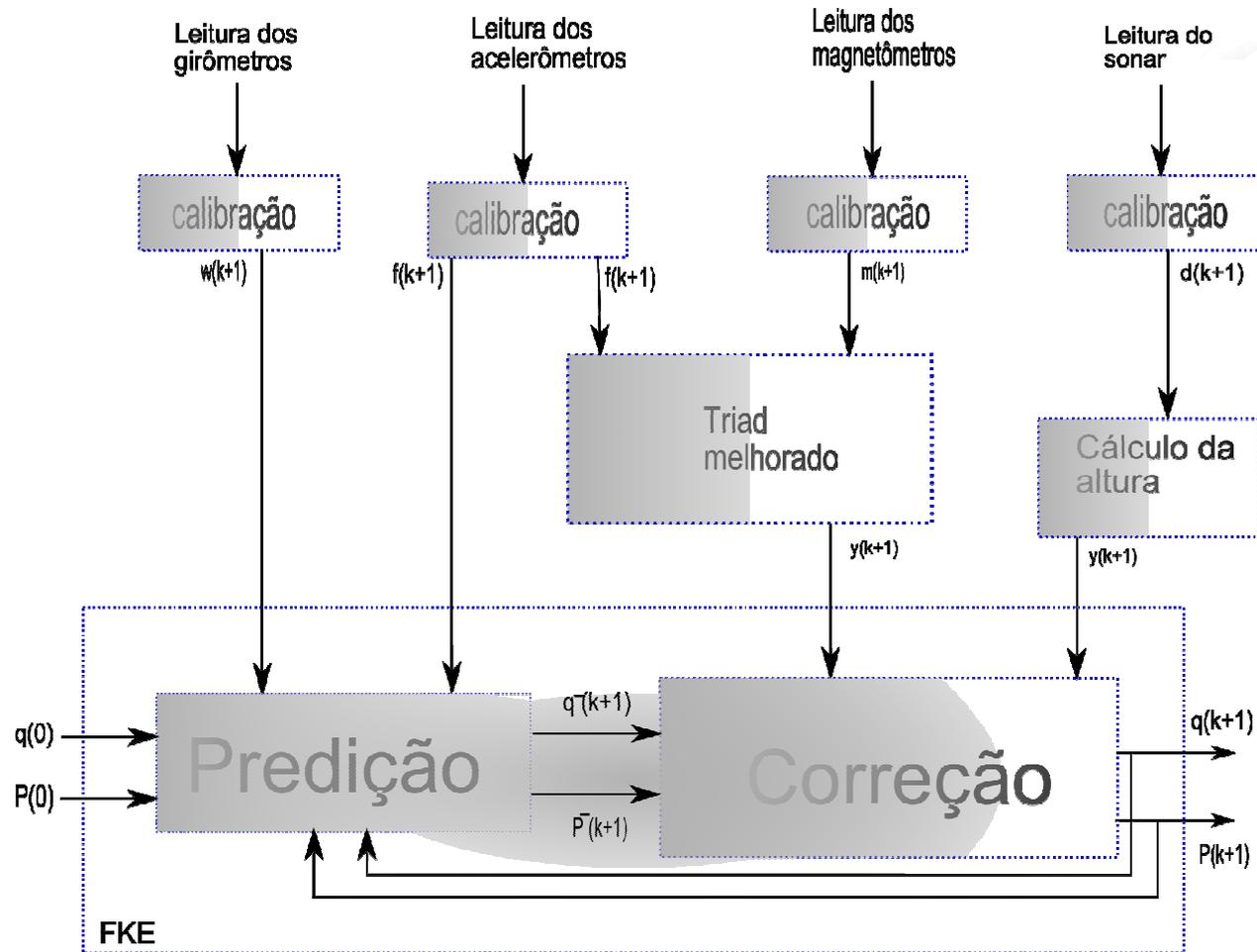
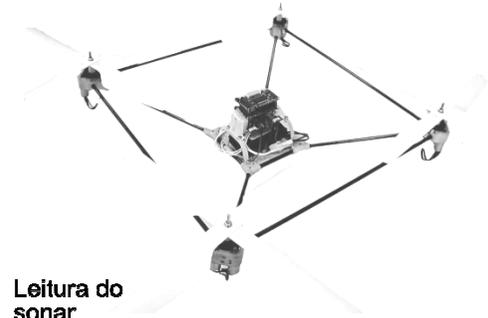
$$v_w = \int_{t_1}^{t_1+T} a_w dt$$
$$r_w = \int_{t_1}^{t_1+T} v_w dt$$

- Altura

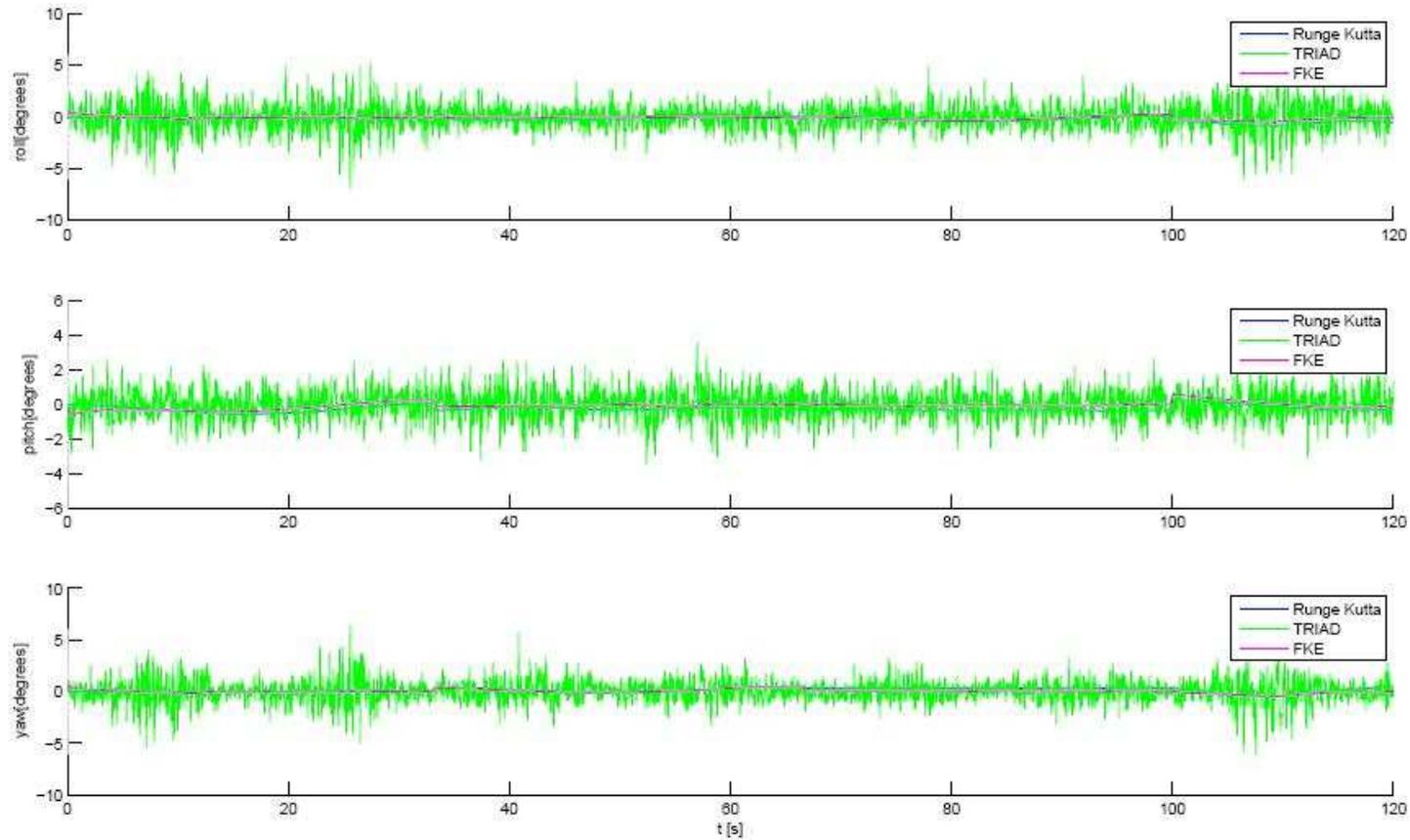
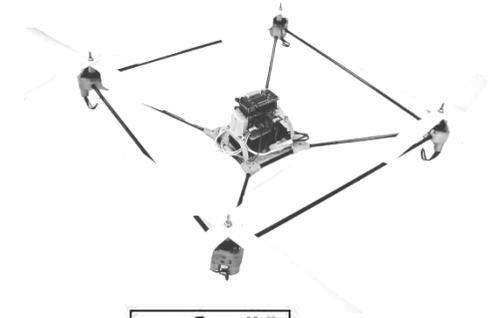
$$d = \frac{h}{a_{33}}$$
$$a_{33} = q_1^2 - q_2^2 - q_3^2 + q_4^2$$



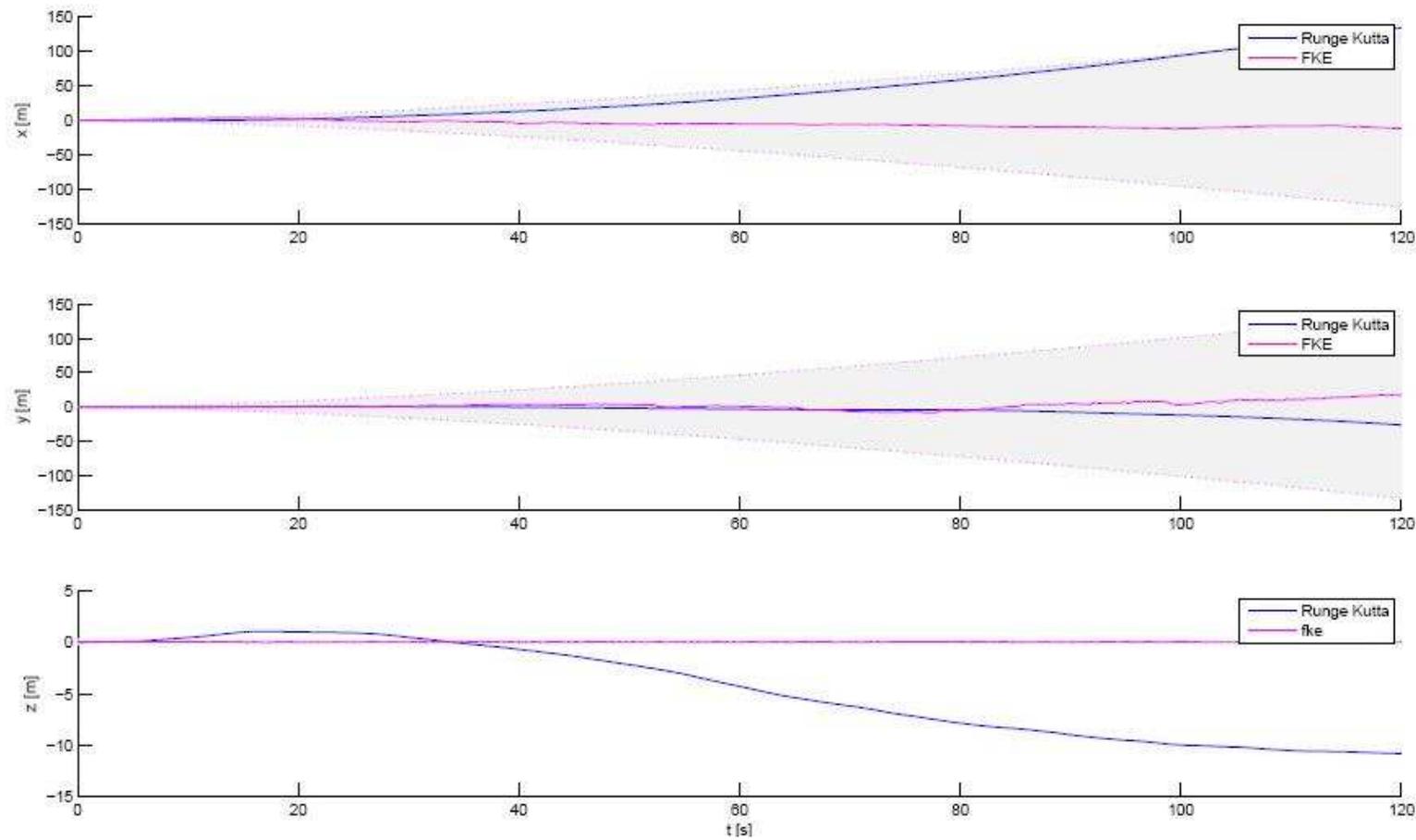
4. Localização



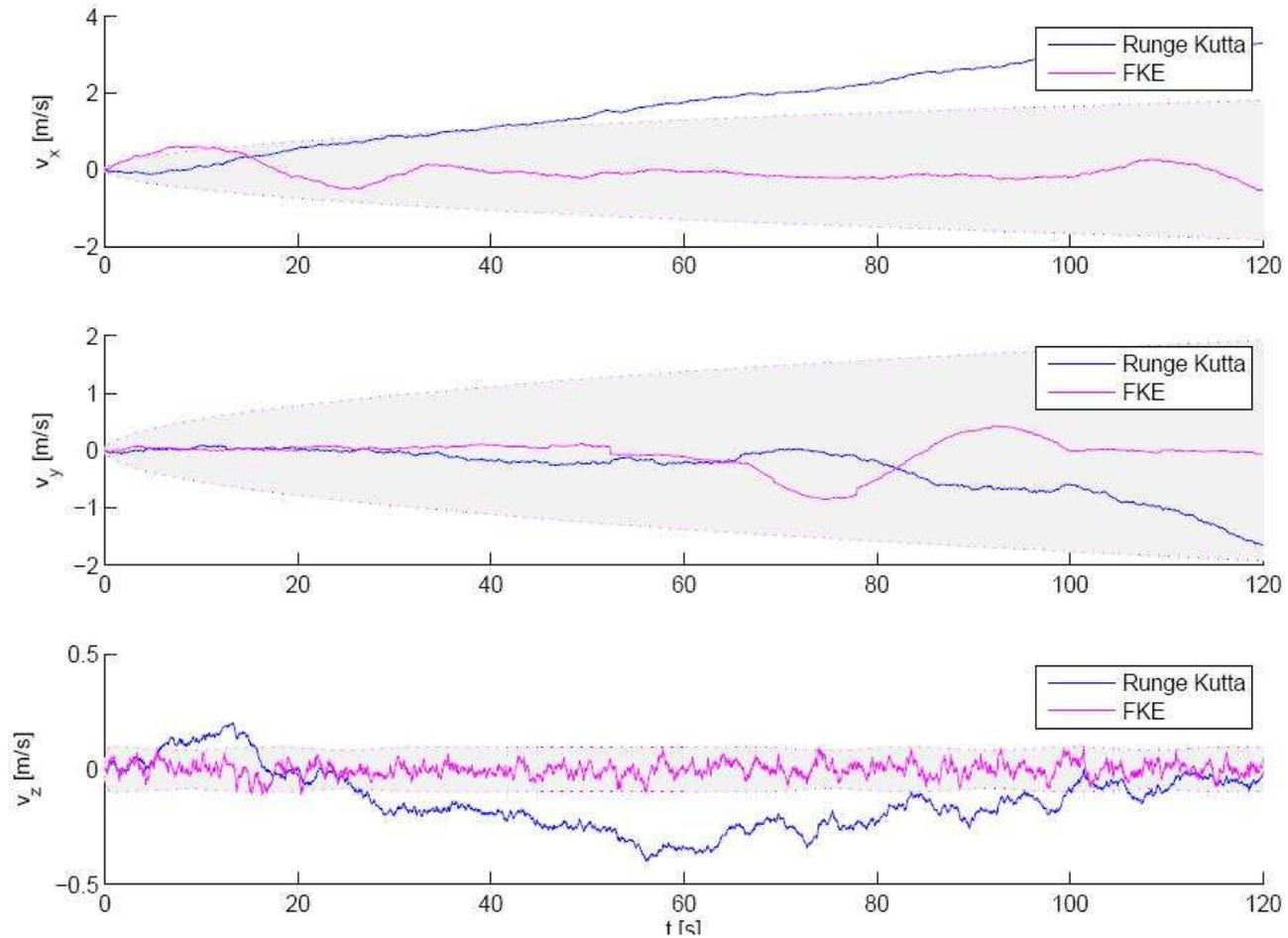
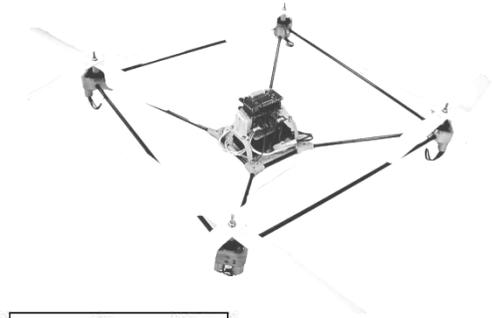
4. Localização



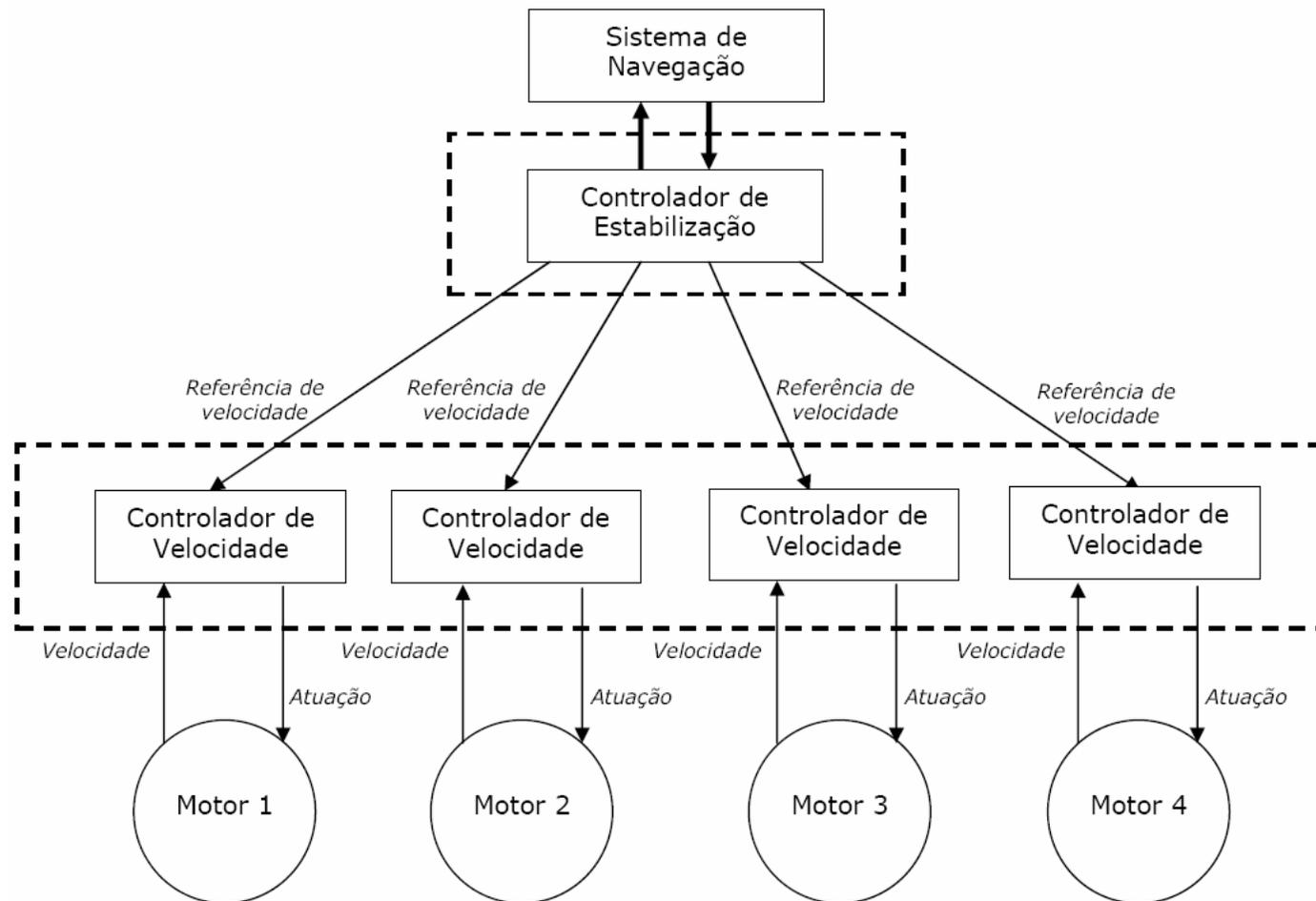
4. Localização



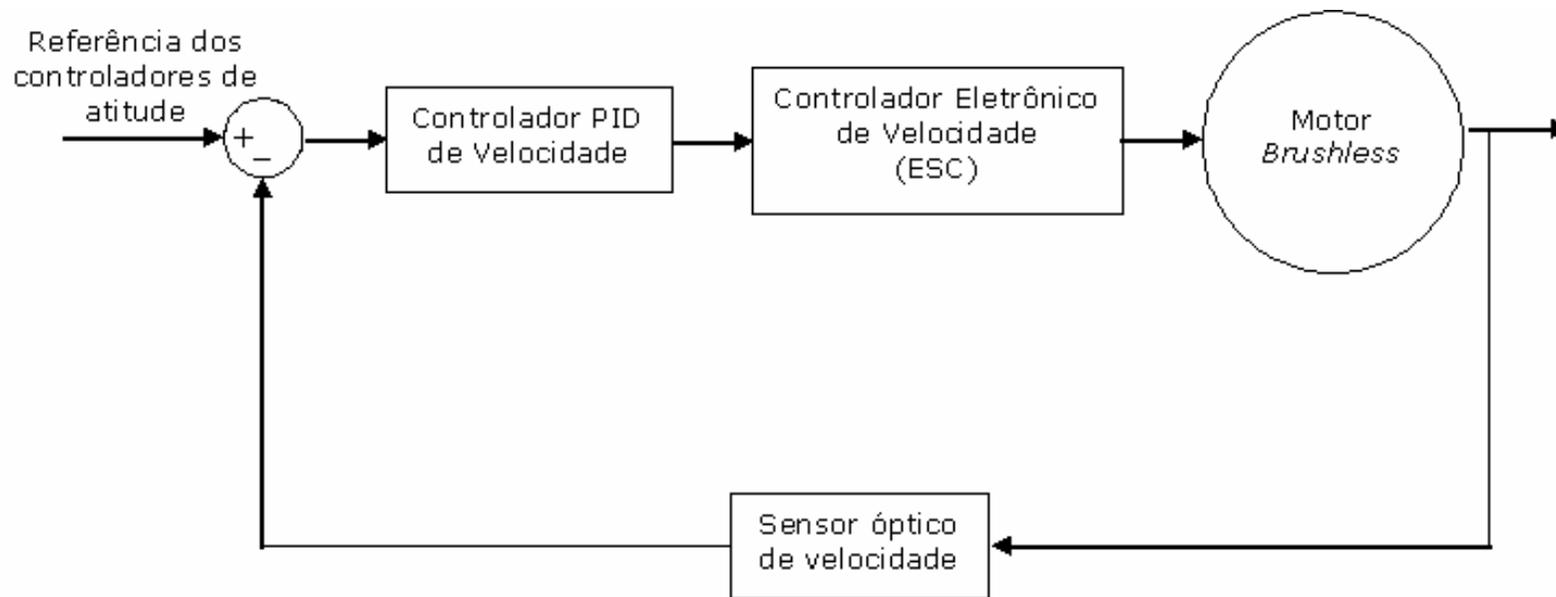
4. Localização



5. Controle



5. Controle



5. Controle

Controle por linearização de modelo em torno de um ponto de operação

$$\delta \dot{x} = \left. \frac{\partial f}{\partial x} \right|_{\substack{x = \bar{x} \\ u = \bar{u}}} \delta x + \left. \frac{\partial f}{\partial u} \right|_{\substack{x = \bar{x} \\ u = \bar{u}}} \delta u$$

- Estabilização do quadricóptero



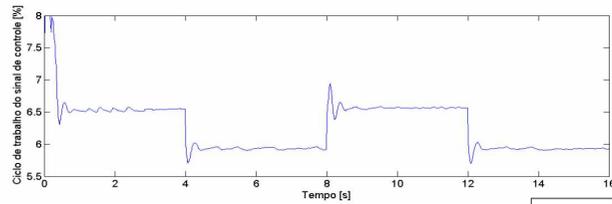
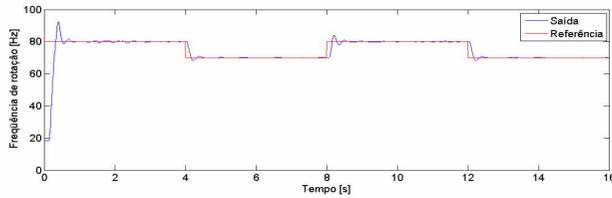
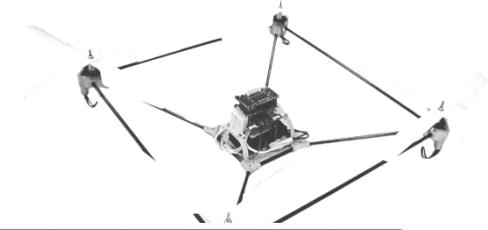
Controle PID

$$u(t) = K_p e(t) + K_i \int_0^t e(x) dx + K_d \frac{de(t)}{dt}$$

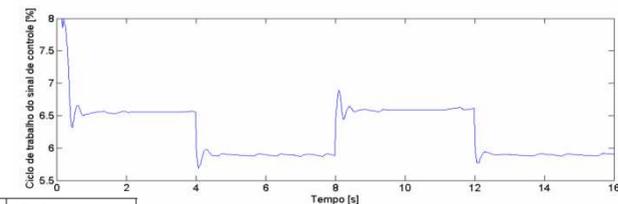
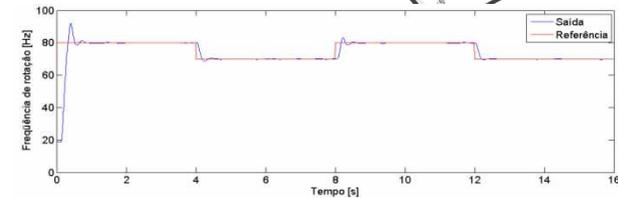
$$\begin{cases} u_i(k) = u_i(k-1) + K_{id} T e(k) \\ u(k) = K_{pd} e(k) + u_i(k) + \frac{K_{dd}}{T} (e(k) - e(k-1)) \end{cases}$$

- Estabilização do quadricóptero
- Controle de velocidade dos motores

5. Controle

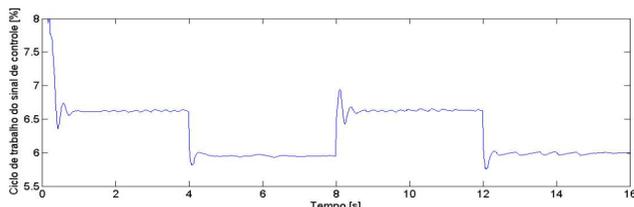
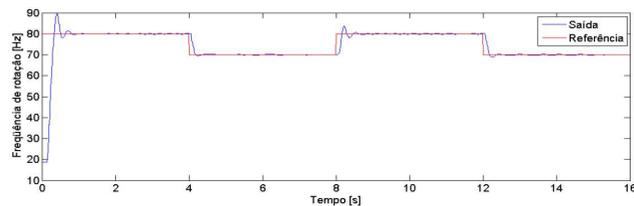


Motor 1

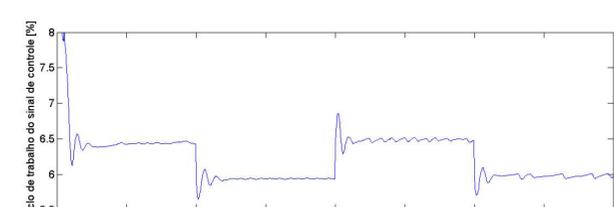
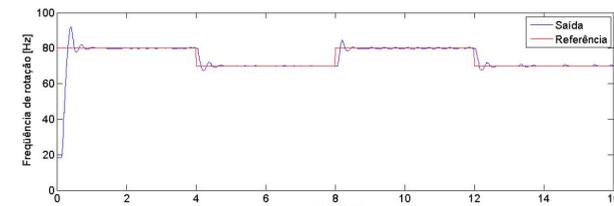


Motor 2

Motor	Tempo de pico [s]	Tempo de acomodação (2%) [s]	Sobrepasso
1	0,20	0,58	40%
2	0,22	0,60	34%
3	0,22	0,61	39%
4	0,20	0,58	45%

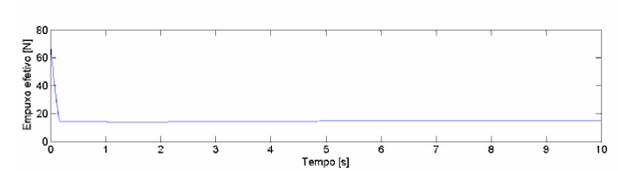
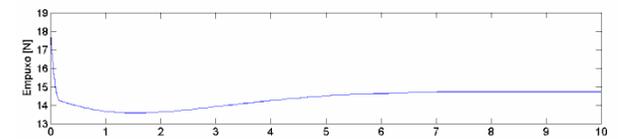
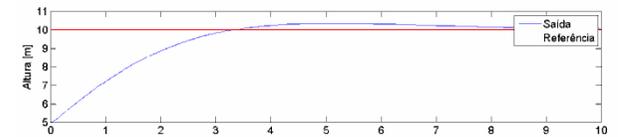
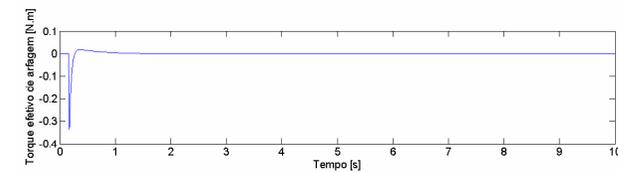
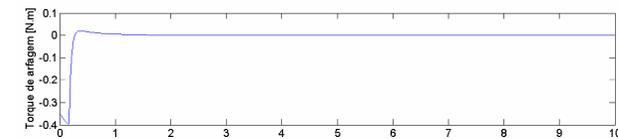
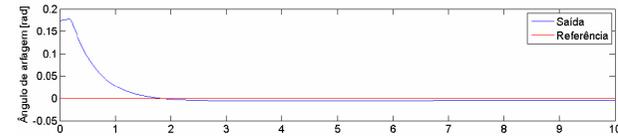
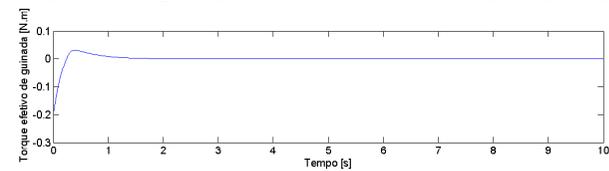
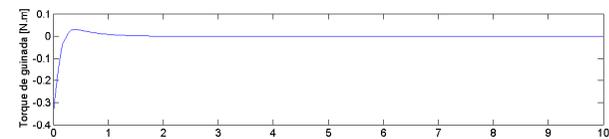
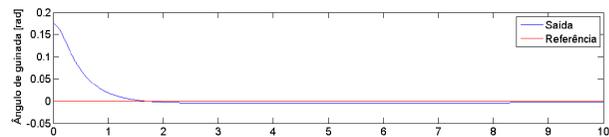
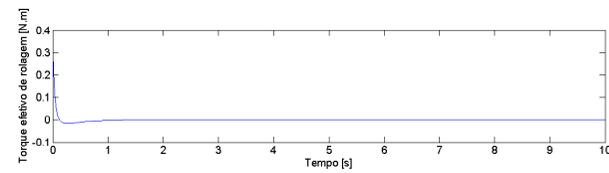
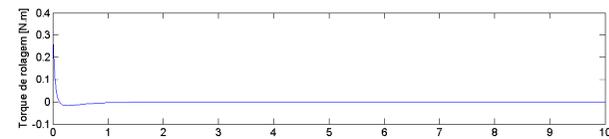
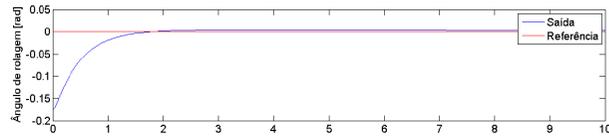
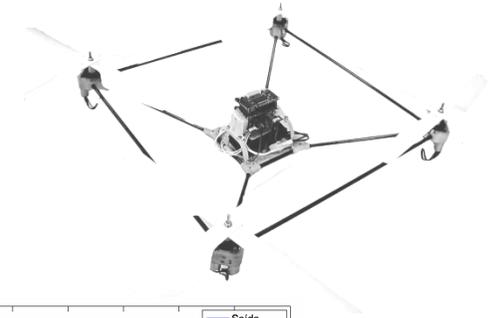


Motor 3



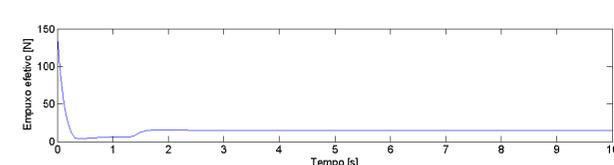
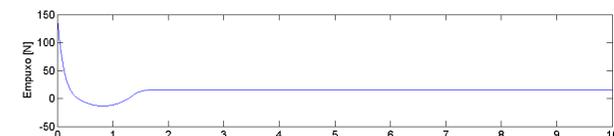
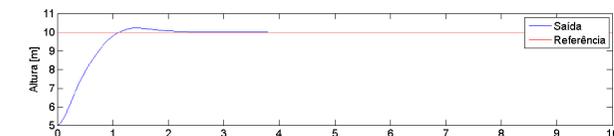
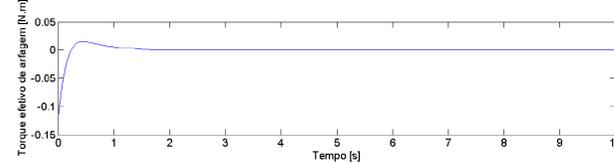
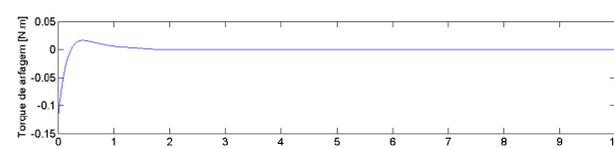
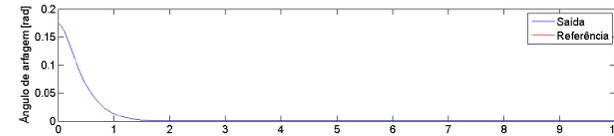
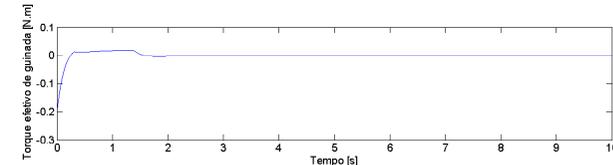
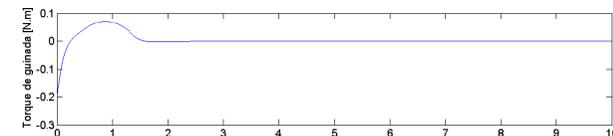
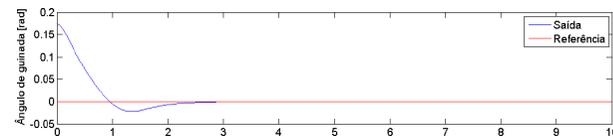
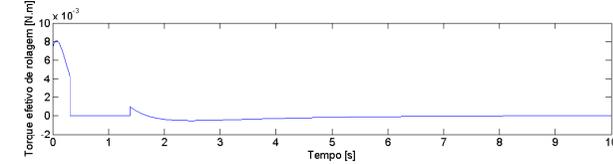
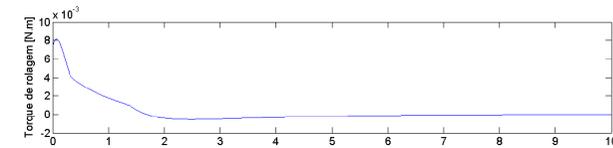
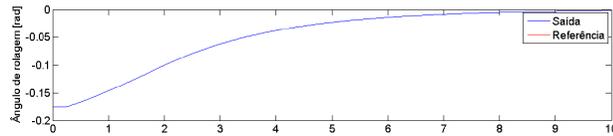
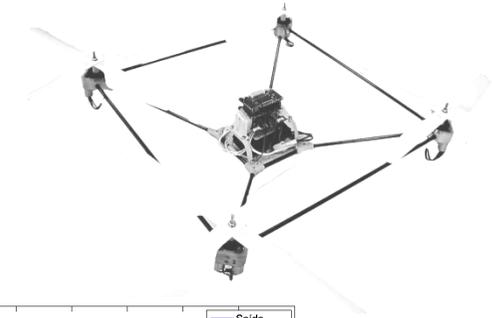
5. Controle

Controladores PID

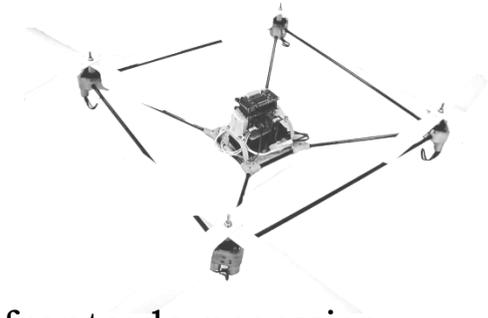


5. Controle

Controlador de modelo linearizado em torno de ponto de operação

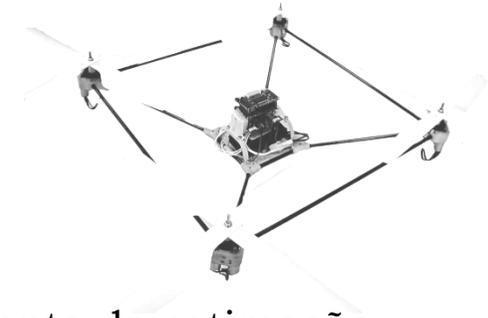


6. Conclusões e propostas para trabalhos futuros



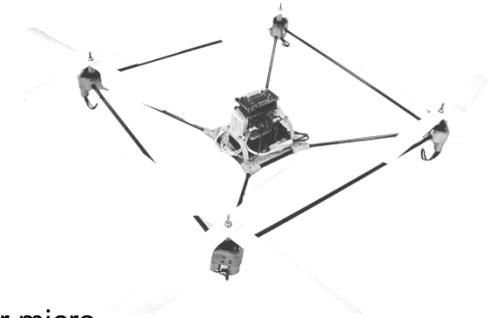
- O presente Trabalho representou a abertura de uma nova frente de pesquisa em robótica aérea no LARA;
- A pedra fundamental de todo o desenvolvimento foi o estudo matemático realizado inicialmente;
- Os simuladores desenvolvidos foram ferramentas de grande importância;
- Obteve-se uma plataforma aérea funcional e versátil, podendo ser útil a futuros projetos na área de robótica aérea;
- Os resultados experimentais confirmam a viabilidade de aplicação das técnicas de estabilização apresentadas;
- A implementação da estimação de estados mostrou-se satisfatória;
- Houve êxito no cumprimento dos objetivos propostos;

6. Conclusões e propostas para trabalhos futuros



- Recomenda-se a fusão de mais sensores para o melhoramento da estimação de estados;
- Otimizar a estrutura mecânica do quadrirrotor;
- Utilizar o modelo matemático identificado do sistema de propulsão para o desenvolvimento de controladores mais eficientes;
- Desenvolver uma interface gráfica mais amigável para os simuladores;
- Aprimorar as interfaces desenvolvidas para a aquisição direta de dados do quadrirrotor pelo MATLAB e para o controle do protótipo via *joystick* convencional;
- Finalizar a integração dos sistemas de controle e de estimação de estado;
- Identificar os parâmetros do modelo dinâmico do quadrirrotor, permitindo que estratégias de controle mais elaboradas sejam utilizadas, como o controle por linearização de modelo apresentado.

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Obrigado!

Dúvidas?