Aalto University
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ORangE

Operational Range Estimation for Mobile Robot Exploration on a Single Discharge Cycle

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Overview

Motivation

Mission Characterization

- Endurance Estimation
- Energy Estimation
- Operational Range Estimation
  - Simplified Range Est. framework
  - Generalized Range Est. framework

Experiments

Summary

References

Motivation

- Mobile robots powered by LiPo batteries
- Recharging usually not possible

***(a)** Delivery robot called Kiwibot.*

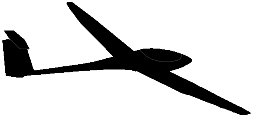
***(b)** Vacuum cleaning robot.*

***Figure 1:** Some recent use-cases of autonomous robots.*

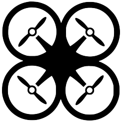
- Ensure safe return to base
  - Hardware failure aside, avoid complete immobilization.

Endurance & Energy Estimation

- Designed primarily for aerial vehicles
- Estimates **max. flight time**
- Constant consumption of kinetic energy, even for hovering



***(a)** Fixed-wing aircraft.*



***(b)** Rotary-winged aircraft.*

***Figure 2:** Endurance estimation for aerial platforms.*

- [Traub, 2013], [Gatti et al., 2015] model only soaring and hovering energy consumption

Endurance & Energy Estimation (cont.)

- Designed primarily for ground robots
- Estimates **mission energy** requirements
- When stationary, only ancillary energy is consumed

Figure 3: *Energy estimation for ground platforms.*

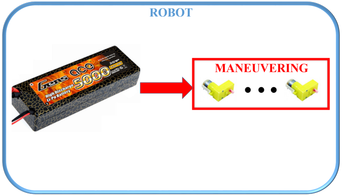
- [Sadrpour et al., 2013] used fixed trajectories

Endurance & Energy Estimation (cont.)

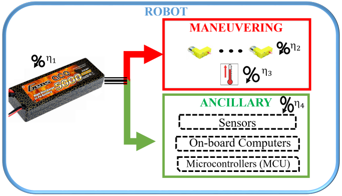
Remarks:

- Fixed trajectories do not cover full maneuvering capabilities
  - May lead to over-/ under- estimating the endurance or energy requirements
- Mission should be adapted as a function of available resources (battery)
  - ***Operational range*** estimation as opposed to energy/endurance estimation
- Also, desirable to have a ***generic framework*** for variety of platforms
- Freedom to ***stop-and-process*** as opposed to incessant motion

Simplified Range Est. framework



(a) *Idealistic model.*



(b) *Realistic model.*

Figure 4: *All energy stored in the battery is used as it is for performing maneuvers in an idealistic battery dissemination model. Battery losses* (η_1)*, maneuvering losses* (η_2, η_3) *and ancillary losses* (η_4)*, however, present in a realistic model.*

Simplified Range Est. framework (cont.)

Residual Energy from Battery [Tiwari et al., 2018]:

$$\hat{E} = E_O \exp^{-(k_1 C + k_2 t)} \tag{1}$$

Energy dissipation model:

$$\begin{aligned}
\hat{E} &= AE + TE\,, \\
&= Ancillary\ Power \times time + \frac{ME}{{}^{r}\Omega_{Man}}\,, \\
&= P_{Anc} \times \frac{d}{v\boldsymbol{D}} + \frac{(C_{rr}\, m_R\, g \cos\theta + cv^2 + m_R\, g \sin\theta)d}{{}^{r}\Omega_{Man}}\,, \\
&= d \times \left\{ \frac{P_{anc}}{v\boldsymbol{D}} + \frac{(C_{rr}\, m_R\, g \cos\theta + cv^2 + m_R\, g \sin\theta)}{{}^{r}\Omega_{Man}} \right\}.
\end{aligned} \tag{2}$$

Simplified Range Est. framework (cont.)

where,

$$P_{Anc} = \underbrace{\{s_0 + s_1 f_s\}}_{P_{Sense}} \tag{3}$$

Thus,

$$d_{max} = \left\{ \frac{\hat{E}}{\frac{P_{Anc}}{v_{opt} D} + \frac{(C_{rr}\, m_R\, g \cos\theta + cv^2 + m_R\, g \sin\theta)}{{}^{r}\Omega_{Man}}} \right\} \tag{4}$$

Generalized Range Est. framework

1. Constant **resistive force** $F(r, m)$, as a function of robot (r) and the mission (m): *e.g.,* the force acting on a robot when it is traversing in a straight line under the influence of a constant magnetic field.
2. **Environment dependent force** $F(x, r, m)$, which is dependent on the current position x: *e.g.,* changing gravitational potential along with changing frictional force because of change in coefficient of friction.
3. **Time dependent resistive force** $F(t, r, m)$, which is a function of current time t: *e.g.,* unforeseeable disturbances (strong wind gusts *etc.*).
4. Instantaneous operational **velocity dependent resistive force** $F(v, r, m)$, which varies with instantaneous velocity v: *e.g.,* aerodynamics and gyro effect.

Generalized Range Est. framework (cont.)

Gen. Traversal energy model [Tiwari et al., 2019]:

$$TE = \frac{ME}{{}^{r}\Omega_{Man}} = \frac{\int\limits_{Path} F_{Net} dx}{{}^{r}\Omega_{Man}} = \frac{\int\limits_{Path} \{F(r,m) + F(x,r,m) + F(t,r,m) + F(v,r,m)\} dx}{{}^{r}\Omega_{Man}} \tag{5}$$

Gen. Ancillary power model:

$$P_{Anc} = \underbrace{\{s_0 + s_1 f_s\}}_{P_{Sense}} + \underbrace{\{P_{Comp} + P_{Comm}\}}_{P_c} \tag{6}$$

Generalized Range Est. framework (cont.)

$$d = \frac{\tilde{E}}{\frac{P_{Anc}}{vD} + \frac{\{F(r,m) + F(v,r,m)\}}{{}^{r}\Omega_{Man}} + \frac{\int\limits_{Path} \{F(x,r,m) + F(\frac{x}{vD},r,m)\}dx}{d\,{}^{r}\Omega_{Man}}} \quad (7)$$

Remarks:

- Need to estimate $\int\limits_{Path} (\cdot)$
  - xORangE where x = online OR offline

Experiments

(a) *Rusti V1.0.* ***(b)*** *Rusti V2.0.* ***(c)*** *AR Drone 2.0.*

Figure 5: *Various custom and commercial robot platforms for empirical validation of range estimators.*

Experiments (cont.)

Table 1: *Range estimation accuracy for proposed estimators*

Method	Trial Type	Range Estimation Accuracy
Simplified	Indoor- offline	$\sim 70\%$
Generalized	Outdoor- offline	82.97%
	Outdoor- online	93.87%

Summary

- Presented ***Simplified*** & ***Generalized*** ORangE
- Duty cycle (D) allows for stopping, if needed
- Performance empirically evaluated on real platforms indoors/outdoors
- Currently only work that allows range estimation for mobile robots

Thank You!!

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