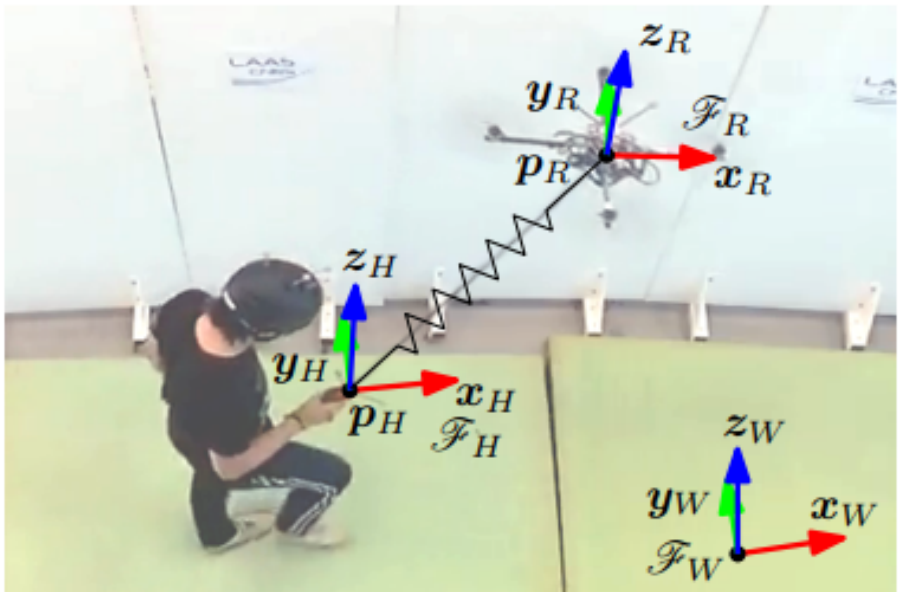
Human State Aware Controller for Tethered UAV

tags: `ResearchPaperNotes`



This paper deals with physical human robot interaction with a tethered UAV. Application to a force based human

We assume a inertial frame $\mathcal{F}_W = \{O_W, x_W, y_W, z_W\}$

where O_W is the arbitrary origin and $\{x_W, y_W, z_W\}$ are unit axes. Z_W is oriented in opposite direction to gravity vector.

$\mathcal{F}_H = \{O_H, x_H, y_H, z_H\}$ We also define a body frame rigidly attached to the handle. O_H is the origin of F_H and $\{x_H, y_H, z_H\}$ are unit axes.

The state of the human is then given by the position of O_H and its linear velocity defined by the vectors

$$p_H = [p_{H_x} \;\; p_{H_y} \;\; p_{H_z}]^T \in \mathbb{R}^3 \;\; and \;\; v_H = [v_{H_x} \;\; v_{H_y} \;\; v_{H_z}]^T$$

Respectively, both with respect to F_W(inertial frame of reference)

The human dynamics are approximated with the mass spring damper system. Impedance model has been used as a basis to develop human robot cooperative task.

We consider the human dynamics as

$m_H \dot{v}_H = -g_H - B_h v_H + f_c + f_g + u_H \;\; g_H = m g_H z_w$

m_h is equal to apparent mass B_h is equal to damping matrix f_c is equal to the cable force applied to the human at O_h u_H is the sum of all the forces applied by the human that generate a translational motion

$f_c = [f_{c_x} \;\; f_{c_y} \;\; f_{c_z}]^T \in \mathbb{R}^3$

g_h is equal to insert eqn f_g is the ground reaction force such that it satisfies these conditions.

- $f_g^T x_W = f_g^T y_W = 0,$
- $f_g^T z_W > 0, and$
- $\dot{v}_H z_W = v_H^T z_W = 0 \;\; i.e., the \;\; human \;\; is \;\; constrained \;\; on \;\; the \;\; ground.$

Therefore the human is constrained on the ground.

Condition for small medium sized aerial vehicles is as follows. inequality $f_c^T z_W < m_H g$

According to equation number 2, the platform is ==infinitely stable== with respect to the interaction forces.

The cable force produced at O_H on the handle

$f_c = t_c(||l_c||)l_c/||l_c|| \qquad -(3)$

where $t_c(||l_c||)$ represents the tension and $l_c = p_R - p_H$.

Force produced on the drone (O_R) is $-f_c$. Cable is considered to be of negligible mass and inertia.

$t_c(||l_c||)$ is given by

$$t_c(||l_c||) = \begin{cases} k_c(||l_c|| - \overline{l_c}) & \text{if } ||l_c|| - \overline{l_c} > 0 \\ 0 & \text{otherwise} \end{cases} \qquad -(4)$$

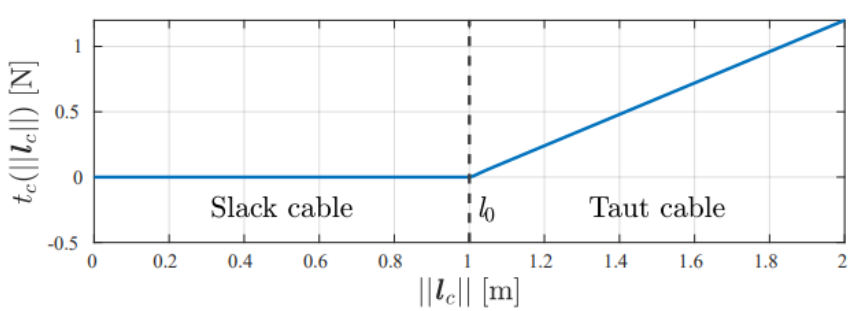


Fig. 2: Representation of $t_c(||\boldsymbol{l}_c||)$ as in (4).

where k_c is constant elastic coefficient.

where t_c can be any continous and differentiable monotonically increasing function.

$t_c(||l_c||) \geq \epsilon||l_c|| + \gamma, \;\; if \;\; ||l_c|| - \overline{l_c} > 0 \qquad -(5)$

Controller

Admittance Control Strategy Admittance is mass, stiffness and damping subjected to the measured external force acting on the robot. Robot control input uR is given by

$\dot{v}_R = M_A^{-1}(-B_A v_R - f_c + u_A + \delta) \qquad -(2)$

where M_A is virtual inertia.

R3 is a bounded variable that takes into account all the tracking errors due to model mismatches and uncertainties, input and state limits, external disturbances, and estimation errors.

Virtual Inertia: As our model is based on spring mass damper system, in 3D we need to assume, 3 different masses in 3 different directions, mutually perpendicular to each other. As these masses do not exist in real time, they are considered as virtual masses connected to 3 different springs in respective directions.

M_A is $5I$ and $B_A = b_A I$ and $B_H = b_H I$ where I is an identity matrix.

In order to implement control law 6, state of the robot (p_R, v_R) and force applied by the cable f_c are required. These two can be computed with onboard sensors. We define the state vector as (state vector x) $x = [p_H^T \;\; v_H^T \;\; p_R^T \;\; v_R^T]^T$

To write the dynamics as $\dot{x}$ equal to $f(x, u_A)$ where

$$\boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u}_A) = \begin{bmatrix} \boldsymbol{v}_H \\ \frac{1}{m_H}\left(-\boldsymbol{g}_H - \boldsymbol{B}_H \boldsymbol{v}_H + \boldsymbol{f}_c + \boldsymbol{f}_g\right) \\ \boldsymbol{v}_R \\ \boldsymbol{M}_A^{-1}\left(-\boldsymbol{B}_A \boldsymbol{v}_R - \boldsymbol{f}_c + \boldsymbol{u}_A\right) \end{bmatrix}$$

$-(5)$

f_c is computed in (3)

The more the human walks fast (modeled as a low damping B_H), the less the force they feel on the cable. Intuitively, looking at (2), the problem comes from the fact that the robot wants to apply the desired force uA but trying to stay still (due to damping term). While the human walks, the two actions are opposite and the system converges to a state where the two are in equilibrium, but none of the two objectives are fully satisfied. To avoid this problem, the robot must consider the human's speed while performing the guiding task.

We propose to modify the control law as

$u_A = K_H e_R + f_c^r + B_A v_H$

kH is proportional gain.

We yield the new robot dynamics as,

$$\dot{\boldsymbol{v}}_R = \boldsymbol{M}_A^{-1}\left(\boldsymbol{B}_A(\boldsymbol{v}_H - \boldsymbol{v}_R) - \boldsymbol{f}_c + \boldsymbol{\Gamma}(\boldsymbol{x})\right).$$

eqn 25
$-(25)$

Therefore the final closed loop dynamics is

$$\boldsymbol{f}(\boldsymbol{x}) = \begin{bmatrix} \boldsymbol{v}_H \\ \frac{1}{m_H}\left(-\boldsymbol{g}_H - \boldsymbol{B}_H\boldsymbol{v}_H + \boldsymbol{f}_c + \boldsymbol{f}_g\right) \\ \boldsymbol{v}_R \\ \boldsymbol{M}_A^{-1}\left(\boldsymbol{B}_A(\boldsymbol{v}_H - \boldsymbol{v}_R) - \boldsymbol{f}_c + \boldsymbol{K}_H\boldsymbol{e}_R + \boldsymbol{f}_c^r\right) \end{bmatrix}. \tag{26}$$

$-(26)$

For simulation:

TABLE I
ADMITTANCE DAMPING GAINS AND THEORETICAL LIMIT AT DIFFERENT WALKING SPEEDS

$\bar{v}_H$ $[\mathrm{m\,s^{-1}}]$	b_H $[\mathrm{kg\,s^{-1}}]$	$4b_H$ $[\mathrm{kg\,s^{-1}}]$	$b_A^{\boldsymbol{\Gamma}_H}$ $[\mathrm{kg\,s^{-1}}]$
0.075	40	160	180
0.1	30	120	100
0.2	15	60	60