Autonomous Robotic Vehicles

Ground, Air, Undersea

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Types of Vehicles

• Ground
  – Wheeled
  – Tracked
  – Legged
  – Crawling/snake

• Air
  – Fixed wing
    • Powered
    • gliders
  – Rotary wing
  – Flapping wing
  – Morphing
  – Airships

• Underwater
  – High speed
  – Glider

• Scales:
  – Large
  – Small
  – Mini
  – Micro
Ground Vehicles

- DARPA Grand Challenge

- Military Applications
  - Perceptor (air-ground autonomous team)

- Automated industrial applications
  - Material handling/delivery
  - Mining
  - Agriculture
  - Mowing
  - Pipeline exploration
Challenges for Autonomous Ground Vehicles

- Operations on uneven/loose terrain
- Ground location is poor position to spot obstacles
- Water hazards difficult to discern
- Precision (localization)
  - Agricultural, mining and mowing applications require cm level precision and accuracy

All of the above limit the safe operational speed achievable with today’s technology

The Level of complexity increases along with the degrees of freedom of the robot
Basics of Ground Vehicle Dynamics
(for a simple robot): 3 DOF

- 3 degrees of freedom (x, y, theta)
- 2 Controls: speed of left and right wheels
  - $\omega(k) = (V_l(k) - V_r(k))/L$
  - $\theta(k) = \theta(k-1) + \omega(k) \Delta t$

- $\Delta X(k) = (V \Delta t) \cos(\theta(k))$
- $\Delta Y(k) = (V \Delta t) \sin(\theta(k))$

where X = location of the robot in fixed X axis
Y = location of the robot in fixed Y axis
theta = orientation of the robot respect to X axis
$\Delta X$ = increment in x per time step
$\Delta Y$ = increment in y per time step
$\Delta \theta$ = increment in $q$ per time step
$V(k) \Delta t$ = displacement of robot in each time step
L = the length between left and right wheels of the robot.

Control is simple but this configuration is not suited for all applications:
- castoring wheels needed for balance may get easily stuck
Trigonometric Function Definitions

\[
\theta
\]

- \(\cos(\theta)\)
- \(\tan(\theta)\)
- \(\sin(\theta)\)
- \(\sec(\theta)\)
- \(\csc(\theta)\)
- \(\cot(\theta)\)

Unit Circle

Radius = 1
Basics of Ground Vehicle Dynamics (for a car-like robot): 3 DOF

- **3 degrees of freedom (x, y, theta)**
- **2 Controls: speed, turning angle**
- \( \Delta \theta(k) = (V(k) \Delta t/L) \tan(\alpha(k)) \)
- \( \theta(k) = \theta(k-1) + \Delta \theta(k) \)
- \( \Delta X(k) = (V \Delta t) \cos(\theta(k)) \)
- \( \Delta Y(k) = (V \Delta t) \sin(\theta(k)) \)

where:
- \( X \) = location of the robot in fixed X axis
- \( Y \) = location of the robot in fixed Y axis
- \( \theta \) = orientation of the robot respect to X axis
- \( \Delta X \) = increment in x per time step
- \( \Delta Y \) = increment in y per time step
- \( \Delta \theta \) = increment in \( q \) per time step
- \( V(k) \Delta t \) = displacement of robot in each time step
- \( \alpha \) = steering angle;
- \( L \) = the length between front and rear wheels of the car-like robot.

**Global State:** \([X,Y,\theta]\)

**Sensor Information**
- \( \psi \): from compass
- \( v, \omega \): from encoders
- \( \lambda \): from GPS – \( \text{atan2}(X,Y) \)

**Estimation of \( \theta \)**

**Kinematic Model**

\[
\begin{align*}
\dot{X} &= v \cos \theta \\
\dot{Y} &= v \sin \theta \\
\dot{\theta} &= \frac{v \tan \alpha}{l} = \frac{v}{R_a} = \omega
\end{align*}
\]
Air Vehicles: 6 DOF

- **Military Applications**
  - Surveillance/tactical

- **Commercial Applications**
  - Agriculture
    - Precision Farming
  - Highway surveying

- **Scientific Application**
  - Ecological surveying

Configurations and applications too numerous to cover in detail
Challenges for Autonomous Air Vehicles:
Many issues still remain despite breakthroughs in technology

- **Power Required to stay aloft**
  - Momentum must be imparted to the air so that the change in the momentum of the air equals the weight of the vehicle: installed power must be sufficient
  - Fuel (electrical or chemical) must be carried: micro air vehicles have time aloft ~ 10-20 minutes

- **Loads due to turbulence**
  - Unsteadiness leads to loads on airframe components
    - Increasing structural strength often requires increasing the mass of the structure… which means it must withstand higher inertial loads… which leads to the requirement for more strength…
      - New material science helps but not eliminates the problem

- **Drift due to winds/currents**
  - Lighter than air vehicles may be directly carried by ambient winds
  - Heavier than air vehicles are dynamically and statically affected by winds

- **Methods of control**
  - Control surfaces must be added to alter the balance of forces on the vehicle to control it

- **Stability**
  - Response modes in each axis must be stabilized

- **Mission sensor fusion** – imaging/localization
Basics of Flight Dynamics

• Forces and moments must be balanced in $3D$ for steady flight
  – Lift is perpendicular to velocity
  – Drag is aligned with velocity but in opposite direction
  – Weight is aligned with gravity vector
  – Propulsive force is typically aligned with the airframe

$\gamma$: flight path angle = angle between level and velocity vector (+pointing above horizon)
$\theta$: pitch angle = angle between aircraft body and level (+pointing above horizon)
$\alpha$: angle of attack = angle between body and velocity vector (+body axis points above velocity vector)

$\alpha = \theta - \gamma$
Straight and Level Flight Cruise Condition
\( (\alpha = \theta = \gamma = 0) \)

- Forces and moments must be balanced in 3D for steady flight
  - Lift = Weight
  - Drag = Propulsive Force

Net acceleration = 0; Normal load (n) factor is defined as the multiple of the maneuver acceleration the vehicle must provide along its z body axis with respect to the magnitude of gravity, so \( n = 1 \, (1g) \) in straight and level flight
Turning Level Flight Cruise Condition

\( (\alpha = \theta = \gamma = 0) \)

**Vertical component of Lift must = mg**

**Horizontal component of Lift provides**

**Turning acceleration** \( a_{cp} = \omega^2 r = V^2/r \)

\[ r = \frac{V^2}{(g\times \tan(\phi))} \]

\[ \omega = \frac{g\times \tan(\phi)}{V} \]

\( n = \frac{1}{\cos(\phi)} \) and has units of g’s

\( g’s = \frac{1}{\cos(\arctan(V^2/(g\times r)))} \)

Angle of bank = \( \arctan(V^2/(g\times r)) \)

- Forces and moments must be balanced in **3D** for steady flight
  - Lift = Weight/cos(\( \phi \))
  - Drag = Propulsive Force
  - Turning acceleration = g*tan(\( \phi \))

Net acceleration = 0; Normal load \((n)\) factor is defined as the multiple of the maneuver acceleration the vehicle must provide along its z body axis with respect to the magnitude of gravity, so \( n > 1 \) \((1g)\) in turning level flight
Basics of Airship Dynamics

- Airships operate at or near neutral buoyancy
  - Lift = mg without any expense of power
  - Rolling airship does not change orientation of lift vector
    - Airships must use sideslip ($\beta$) to turn
      - Thrust ($T$) must increased during turn if airspeed is to be held constant
      - “Passengers” will feel lateral forces in turns (centrifugal force)
  - Neutral buoyancy means the ship is carried instantaneously by the wind

$$T\sin(\beta)$$ provides centripetal acceleration

Circumference of Turn

top view
Basics of Underwater Dynamics

• Same principle as airships but water density is much higher
  – High power needed to counter water currents/tides (viscous force much higher)
  – Low powered gliders exploit buoyancy for propulsion – flying through the water
    • Change buoyancy by pumping water
    • Move a control mass inside of hull to dynamically change inertia
Challenges for Autonomous Undersea Vehicles

Undersea vehicles have specific challenges *in addition* to those of both ground and air vehicles

- Power Required to counter currents (operate in rivers or tidal areas)
- Localization sensing is complex
  - GPS unavailable; sonar is primary sensor
- Communication with surface is difficult
  - Radio frequency communication not possible
  - Acoustic modems are relatively low range and low bandwidth
- Operations may require hardening hull to withstand extreme pressures
Complexity of fielded robots much higher than discussed here:

- Typically there is more than one actuator for each motion DOF
  - Complex coordination required to avoid “force fighting”
  - Actuator configuration not unique
  - Actuator motion not directly linked to a control axis
- Sensors typically use multiple modes for each state
- Vehicle is never really a rigid body
  - Flexible modes must be accounted so that vehicle does not become unstable
- Power and endurance are limited
References for Further Study

• Internet:
  – Autonomous UGVs: [www.ri.cmu.edu/people/stentz_anthony.html](http://www.ri.cmu.edu/people/stentz_anthony.html)
  – Underwater AUV’s: [http://spray.ucsd.edu/](http://spray.ucsd.edu/)

• Texts:
    check out all the books available though Parallax…

• Magazines:
  – Nuts and Volts ([http://www.nutsvolts.com/](http://www.nutsvolts.com/)) ← very good source of information for the hobbyist…
News Item…

By AUVSI Staff

Bullish Market for UAVs  Worldwide UAV Market to Top $30 Billion

Unmanned Aerial Vehicles (UAVs) continue to be the most dynamic growth sector of the world aerospace industry. A Teal Group market study estimates that UAV spending will more than double over the next decade from current worldwide UAV expenditures of $2 billion annually to $4.5 billion within a decade, totaling over $30 billion in the next ten years.