Simulator Control Via Wireless Data Glove

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Overview

- Introduction
- Texas A&M Flight Simulation Laboratory
- VisNav System Overview
- Data Glove – Command Generation
- Controller Development
- Glove – PC Interface
- Conclusion & Ongoing Work
Introduction

Glove Applications

Air Traffic Control

Flight Simulation

UAV Piloting

Sign Language Interpretation
Introduction

Concept
• Flight simulator command generation via vision-based data glove
• Utilize existing VisNav technology developed at Texas A&M University

Goal
• Demonstrate an effective and intuitive alternative to traditional stick and rudder piloting

Sponsor
• State of Texas Advanced Technology Program
TAMU Flight Simulation Laboratory

- **Fixed-base:** Commander 700; AV-8A Harrier, F-5A Freedom Fighter
  - SGI Onyx Reality II sim engine
  - Networked bank of PC’s
  - Center stick; sidestick
- **155° projected field of view**
  - 30 Hz refresh rate
- **Programmable Head Up Display**
TAMU Flight Simulation Laboratory (cont.)

- Head Down Displays (HDD)
  - Reconfigurable
  - CRT; touchscreen LCD

- Autopilot
  - Glide slope capture
  - Heading
  - Altitude
  - Pitch attitude

- Flight Management System (FMS)
  - Jeppesen data base
  - Pre-flight planning and enroute updating
  - Moving map display
VisNav System Overview

- Analog Line-of-Sight Sensor
- Position Sensing Diode (PSD)
  - Current Imbalance
  - Light Centroid Location
- Beacons & Beacon Controller
  - Array of light emitting diodes (LEDs)
  - Control intensity and sequence
- Digital Signal Processor (DSP)
  - Executes the numerical algorithms
  - Calculates the 6-DOF positions and attitudes
- Ideal pin hole camera model
  - colinearity equations
- Line-of-sight vector observations
- 4 or more beacons with known locations
VisNav System Overview

positions and attitudes

PSD Sensor

Beacons

PSD sensor output

\[ V_y = K \frac{I_R - I_L}{I_R + I_L} \sim \frac{y - y_o}{s_y} = \overline{y} \]
\[ V_z = K \frac{I_U - I_D}{I_U + I_D} \sim \frac{z - z_o}{s_z} = \overline{z} \]

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VisNav Hardware

PSD Sensor

- Wide angle lens focuses wide field of view onto PSD
- Approximately 3” x 3” x 3”

SmartLite Beacons
Adapting VisNav for the Data Glove

<table>
<thead>
<tr>
<th>Current System</th>
<th>Data Glove System</th>
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<tbody>
<tr>
<td>• Single Sensor</td>
<td>• Stereo Sensors</td>
</tr>
<tr>
<td>• Positions &amp; Attitudes between two planes</td>
<td>• Line-of-Sight Vector to each beacon</td>
</tr>
<tr>
<td>• Beacon locations are known w.r.t the beacon reference frame</td>
<td>• Triangulation gives (x,y,z) position of beacon w.r.t sensor coordinate system</td>
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<tr>
<td></td>
<td>• Allows non-planar beacon movements</td>
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VisNav System Overview

cooperative vision

- **Current VisNav Features**
  - *High accuracy*
    - $\approx 1 \text{ mm}/0.05 \text{ deg}$ at distances up to 0.5 m
  - *High data refresh rate*
    - 100Hz
  - *Does not use pattern recognition*

- **Why use Stereo VisNav for Glove-Based Applications?**
  - *Joint angles calculated independent of each other*
    - Strain Gauge and Optical Fibers can introduce joint-to-joint error buildup
  - *High Accuracy Position and Attitudes*
    - Magnetic Field and Ultrasonic Sensors tend to have low resolution
  - *Low Latency*
Beacon Position Triangulation

- Elevation and azimuth angle from each sensor
  - Determine line-of-sight vector to each beacon
- Beacon is located at the intersection of the two vectors

\[
\begin{align*}
\mathbf{c}_1 &= \mathbf{o}_1 + p_1 \mathbf{u}_1 \\
\mathbf{c}_2 &= \mathbf{o}_2 + p_2 \mathbf{u}_2
\end{align*}
\]

Constrained by:

\[
\begin{align*}
(\mathbf{c}_2 - \mathbf{c}_1) \cdot \mathbf{u}_1 &= 0 \\
(\mathbf{c}_2 - \mathbf{c}_1) \cdot \mathbf{u}_2 &= 0
\end{align*}
\]

Unknowns: \( p_1 \) and \( p_2 \)

\[
\begin{align*}
p_1 (\mathbf{u}_1 \cdot \mathbf{u}_1) - p_2 (\mathbf{u}_1 \cdot \mathbf{u}_2) &= \mathbf{o}_2 \cdot \mathbf{u}_1 - \mathbf{o}_1 \cdot \mathbf{u}_1 \\
p_1 (\mathbf{u}_1 \cdot \mathbf{u}_2) - p_2 (\mathbf{u}_2 \cdot \mathbf{u}_2) &= \mathbf{o}_2 \cdot \mathbf{u}_2 - \mathbf{o}_1 \cdot \mathbf{u}_2
\end{align*}
\]

Simultaneously Solve

\[
\mathbf{m} = \frac{1}{2} (\mathbf{c}_1 + \mathbf{c}_2)
\]

Estimated Beacon Location
Glove Orientation Equations

General Glove Rotation

Transformed Orientation

LED 2

LED 3

LED 1

LED 4

LED 1

LED 3

LED 2

LED 4

\[ \hat{e}_1 = \frac{[x_2, y_2, z_2] - [x_1, y_1, z_1]}{\text{norm}([x_2, y_2, z_2] - [x_1, y_1, z_1])} \]

\[ \hat{e}_2 = \frac{[x_4, y_4, z_4] - [x_1, y_1, z_1]}{\text{norm}([x_4, y_4, z_4] - [x_1, y_1, z_1])} \]

\[ \hat{e}_3 = \hat{e}_1 \times \hat{e}_2 \]
Glove Orientation Equations (cont.)

Definition of the Rotation Matrix:

\[
R = \begin{bmatrix}
\hat{b}_1 \cdot \hat{e}_1 & \hat{b}_2 \cdot \hat{e}_1 & \hat{b}_3 \cdot \hat{e}_1 \\
\hat{b}_1 \cdot \hat{e}_2 & \hat{b}_2 \cdot \hat{e}_2 & \hat{b}_3 \cdot \hat{e}_2 \\
\hat{b}_1 \cdot \hat{e}_3 & \hat{b}_2 \cdot \hat{e}_3 & \hat{b}_3 \cdot \hat{e}_3
\end{bmatrix}
\]

\[\theta = \text{atan} \left( \frac{R_{12}}{R_{11}} \right)\]
\[\phi = a \sin \left( -R_{13} \right)\]
\[\psi = \text{atan} \left( \frac{R_{23}}{R_{33}} \right)\]

- Take the three Euler angles from the glove and use these to command the basic roll, pitch, and yaw of the aircraft
- This will require a controller that will allow states to be commanded
- A **Nonzero Setpoint** (NZSP) controller was chosen as our initial controller
Nonzero Setpoint

problem statement

The standard Linear Quadratic Regulator (LQR) problem is:

\[ \dot{x} = Ax + Bu \quad \text{with} \quad x(0) = x_0 \]

Find \( u \) that minimizes \( J = \frac{1}{2} \int_{0}^{\infty} [x^T Q x + u^T R u] dt \)

This can be modified slightly to allow us to command the system to a new steady-state:

\[ \dot{x} = Ax + Bu \quad \text{(System)} \]
\[ y = Hx + Du \quad \text{(Output)} \]

Find \( u \) that will drive \( y \) to a constant \( y_m \) as \( t \to \infty \).
Nonzero Setpoint

time domain block diagram

There are three restrictions on the possible commanded trim states.

1. The rate of a variable cannot be commanded with NZSP.
2. The maximum number of outputs which can be driven to a constant value is equal to the number of control inputs.
3. This system must be controllable, in other words the controls must be able to influence the commanded states.
Nonzero Setpoint

C-700 Simulation – Example

Goal:
• Map the glove orientation angles into commanded vehicle states and controls

\[
y_m = \begin{bmatrix} \phi \\ \delta_r \\ \theta \end{bmatrix} \quad \leftarrow \text{GLOVE EULER ANGLES} \quad \begin{bmatrix} \phi \\ \psi \\ \theta \end{bmatrix}
\]

• Lateral/Directional Commands:
  • Bank Angle Input of 30 deg.
• Longitudinal Commands:
  • Pitch Attitude Angle Input of 9 deg.

Rockwell Commander 700
Cruise Condition Linear Models
• Altitude: 8500 feet
• Airspeed: 122 kts
Nonzero Setpoint

C-700 Simulation – Lateral/Directional

\[ \beta \text{ (deg)} \]
\[ p \text{ (deg/sec)} \]
\[ r \text{ (deg/sec)} \]
\[ \psi \text{ (deg)} \]
\[ \delta_a \text{ (deg)} \]

C-700 Response

Glove Commands

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Nonzero Setpoint
C-700 Simulation - Longitudinal

- $u$ (fps)
- $\alpha$ (deg)
- $\dot{q}$ (deg/sec)
- $\theta$ (deg)
- $\delta$ (deg)

C-700 Response
Glove Commands
VisNav PC Interface

• LabWindows/CVI® Program
• Receives input from DSP via RS-485/RS-232 connection
• Sends commands over a TCP connection to the Flight Simulation Server
Summary

A candidate alternative to stick and rudder or joystick piloting was developed utilizing a vision-based data glove for command input.

Completed Tasks Include:
- Glove Prototype Built
- Sensors Built and Tested
- Sensor Stand Built
- TCP/IP Interface Designed
- Beacon Controller Circuit Built
- Controller Designed

Ongoing Tasks Include:
- Complete DSP Programming for Stereo VisNav
- Calibration of Stereo Sensors
- Finalize Simulator Code & Implementation
- System Demonstration expected – Fall 2003

Future Work Includes:
- Expansion of the Glove Command Lexicon
- Addition of Beacons to Fingers
Questions?
Nonzero Setpoint

problem statement

- At the new steady-state trim point, $x = x^*$, and $u = u^*$. Therefore:
  \[
  \dot{X}^* = AX^* + BU^* \equiv 0
  \]
  \[
  y_m = HX^* + DU^*
  \]

- We now can define new variables
  \[
  \tilde{x} = x - x^* \quad \text{and} \quad \dot{\tilde{x}} = \dot{x} - \dot{x}^* = Ax + Bu - (Ax^* + Bu^*)
  \]
  \[
  \tilde{u} = u - u^* \quad \text{and} \quad \dot{\tilde{x}} = A\tilde{x} + B\tilde{u}
  \]

- Note that $\tilde{x}$ and $\tilde{u}$ are the error between the actual values and the commanded trim point values. Our objective is to drive these errors to zero.

- We can modify the LQR cost function:
  \[
  J = \frac{1}{2} \int_0^\infty \left( \tilde{x}^T Q\tilde{x} + \tilde{u}^T R\tilde{u} \right) dt
  \]

- Since our new control problem fits the standard LQR structure – we already know the solution.
Nonzero Setpoint

problem statement in terms of LQR

Given \( \dot{x} = Ax + Bu \), determine \( \tilde{u}(t) \) that minimizes the quadratic cost function

\[
J = \frac{1}{2} \int_0^\infty \left( \dot{x}^T Q \dot{x} + \tilde{u}^T R \tilde{u} \right) dt
\]

with solution \( \tilde{u} = -K\dot{x} \)

\[
= -R^{-1}B^T P\dot{x}
\]

which satisfies \(-PA - A^T P + PBR^{-1}B^T P - Q = 0\)

Since \( \dot{x} \) and \( \tilde{u} \) are meaningless to the real system we must convert back to the original \( x \) and \( u \) variables:

\[
\tilde{u} = u - u^* \quad \rightarrow \quad u = \tilde{u} + u^*
\]

\[
\dot{x} = x - x^* \quad \rightarrow \quad x = \dot{x} + x^*
\]

Now we substitute these back into the LQR optimal control:

\[
u = u^* - K(x - x^*) \quad \rightarrow \quad u = (u^* + Kx^*) - Kx
\]

constant \quad \quad LQR
Nonzero Setpoint
trim states and controls

All that remains is to determine the values of $x^*$ and $u^*$. These new trim states and trim controls must satisfy the trim equations

$$Ax^* + Bu^* = 0$$
$$Hx^* + Du^* = y_m$$

Solving:

$$\begin{bmatrix} x^* \\ u^* \end{bmatrix} = \begin{bmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{bmatrix} \begin{bmatrix} 0 \\ y_m \end{bmatrix}$$

$$x^* = X_{12}y_m$$
$$u^* = X_{22}y_m$$

Substituting for $x^*$ and $u^*$ in the control implementation equation results in the NZSP control input:

$$u = (X_{22} + KX_{12})y_m - Kx$$

1. A unique solution for $x^*$ and $u^*$ exists only if the quad partition matrix is non-singular, therefore the QPM must be square.
2. The existence of the inverse of the QPM matrix requires that the set of equations for $x^*$ and $u^*$ must be linearly independent.
3. The maximum number of outputs which can be driven to a constant value is equal to the number of control inputs.

$$x^* \in \mathbb{R}^{nx1}, \quad u^* \in \mathbb{R}^{ux1}, \quad y_m \in \mathbb{R}^{px1}, \quad A \in \mathbb{R}^{nxn}, \quad B \in \mathbb{R}^{nxm}, \quad H \in \mathbb{R}^{pxn}, \quad D \in \mathbb{R}^{pxm}$$