Fault Immune Flight Control System for Civil Transports - Double Layered Reconfiguration

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at TBC

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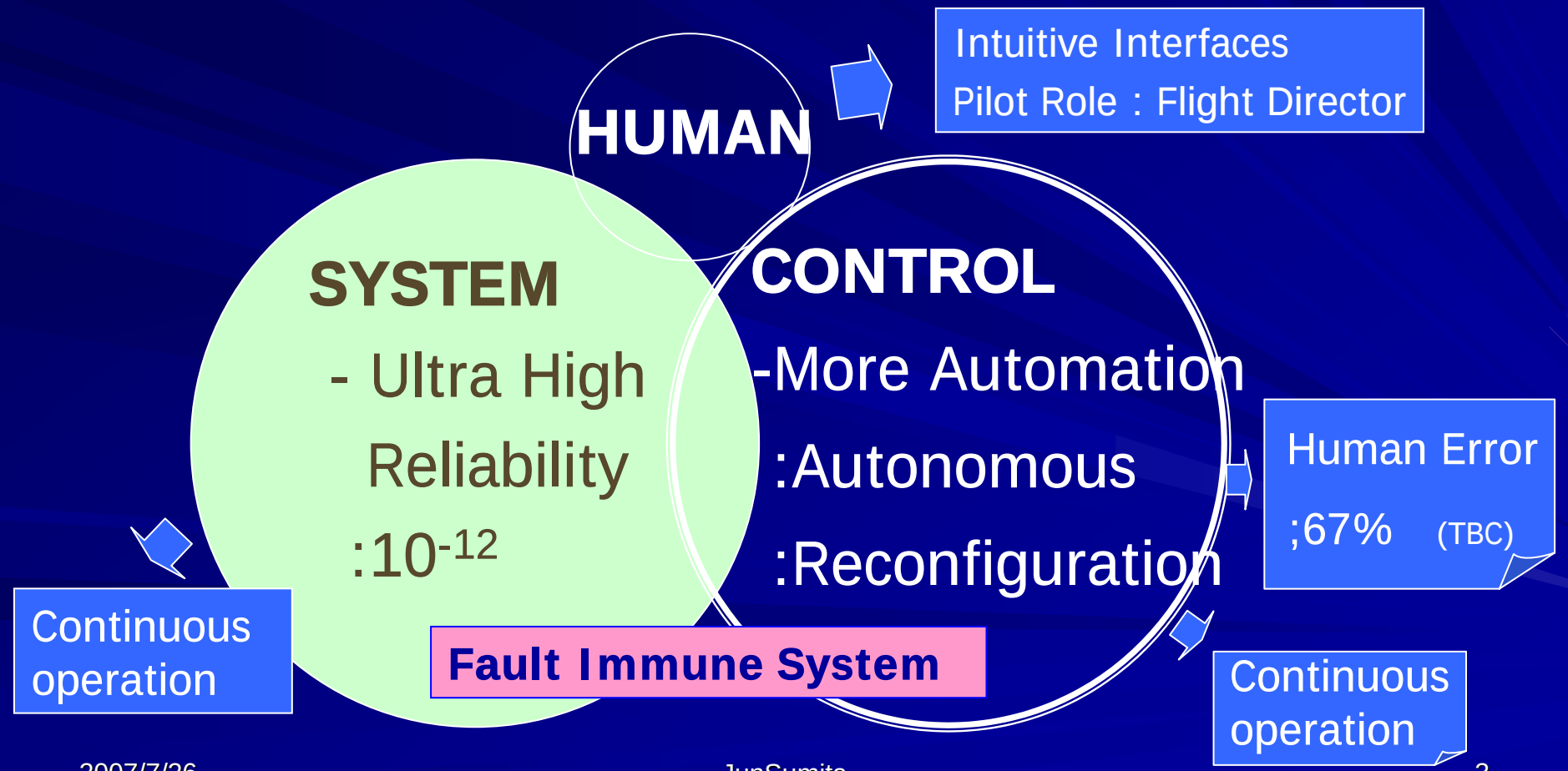
Presentation Flow

- Concept
- Fault Immune System
- Double Layered Reconfiguration Control
- Single Pilot Operation
- Conclusions

General Discussion on -Fault Immune Total Aircraft System

- "Min. Human Interfaces" is an important approach



Concept for " Fault Immune A/C "

- Overcoming faults, such as
  - mal-functions or failures of every aircraft system,
  - failures in aircraft configuration,
  - human-errors, etc.

  , and could be active as normal
- Continuous Safe-Operation with 10^{-12} level of reliability
  - in any conditions
  - under ATC communication

System Structure **-for FCS**

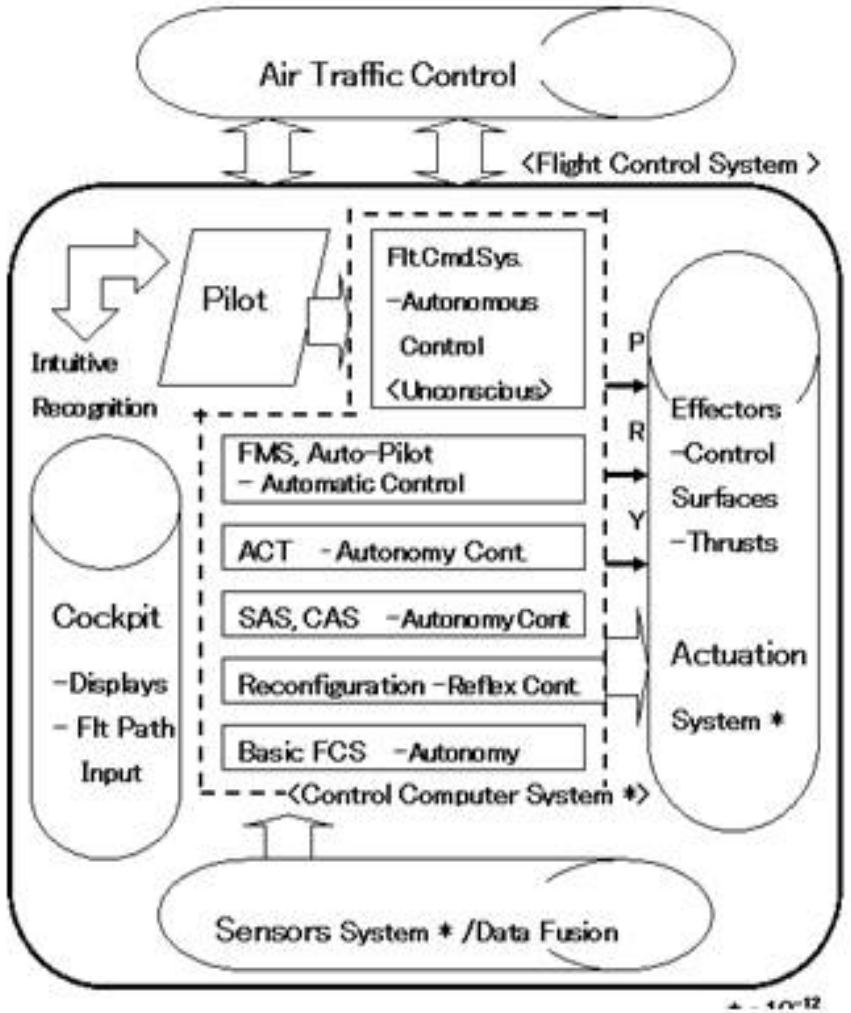
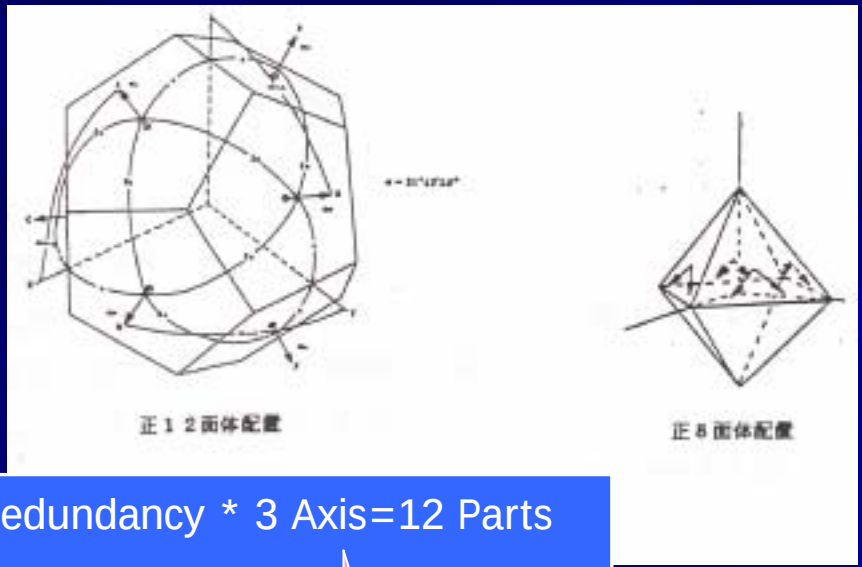


Fig. 2 Structure Concept for the

Sensors of the System (1)

Current status:
Strapdown + Skew

- Skewed Array Sensor / Parity Check



4 Redundancy * 3 Axis=12 Parts
➡ 6 Parts

Measurement: $m = H \cdot w + e$

Parity = $V \cdot e$

where $V \cdot H = 0$

H : Form Matrix

w : 3 Axis Transform. Factor

e : Noise

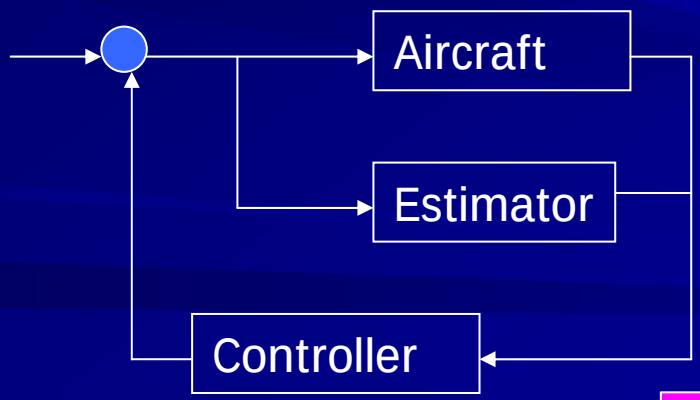
If $m = Hw + e + \underline{e_j b}$

$P = Ve + \underline{V_j b}$

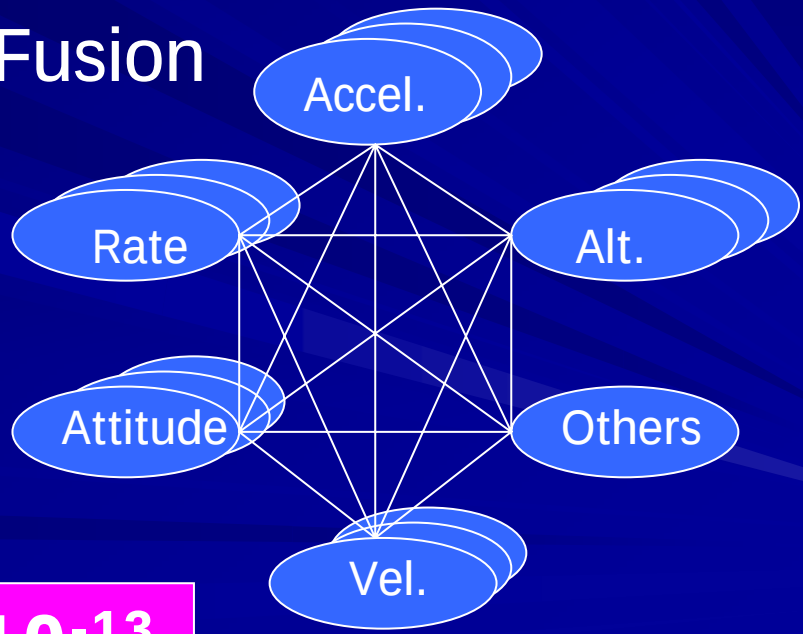
➡ **; 10^{-13}**

Sensors of the System (2)

- Virtual/Analytical Redundancy
  - State Observer
  - Kalman Filter



- Integrated Sensor System
  - Redund. Managemt with Virtual Sensor
  - Fusion

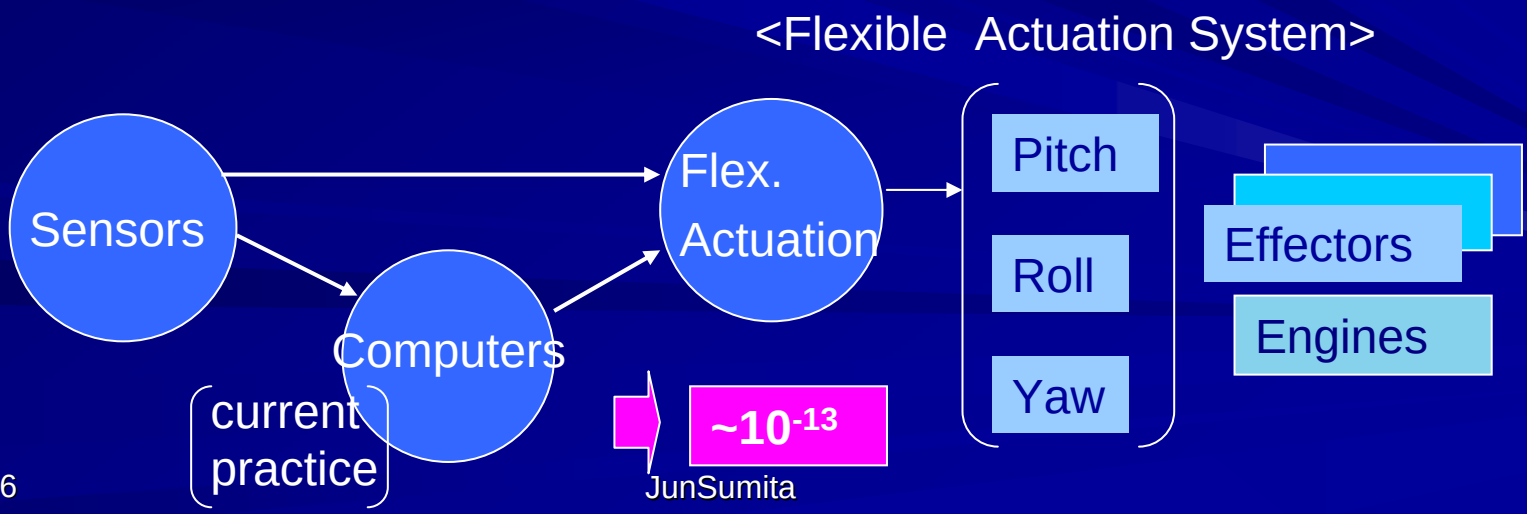


10^{-13}

Actuators / Computers of the System

; Flexible Actuation System

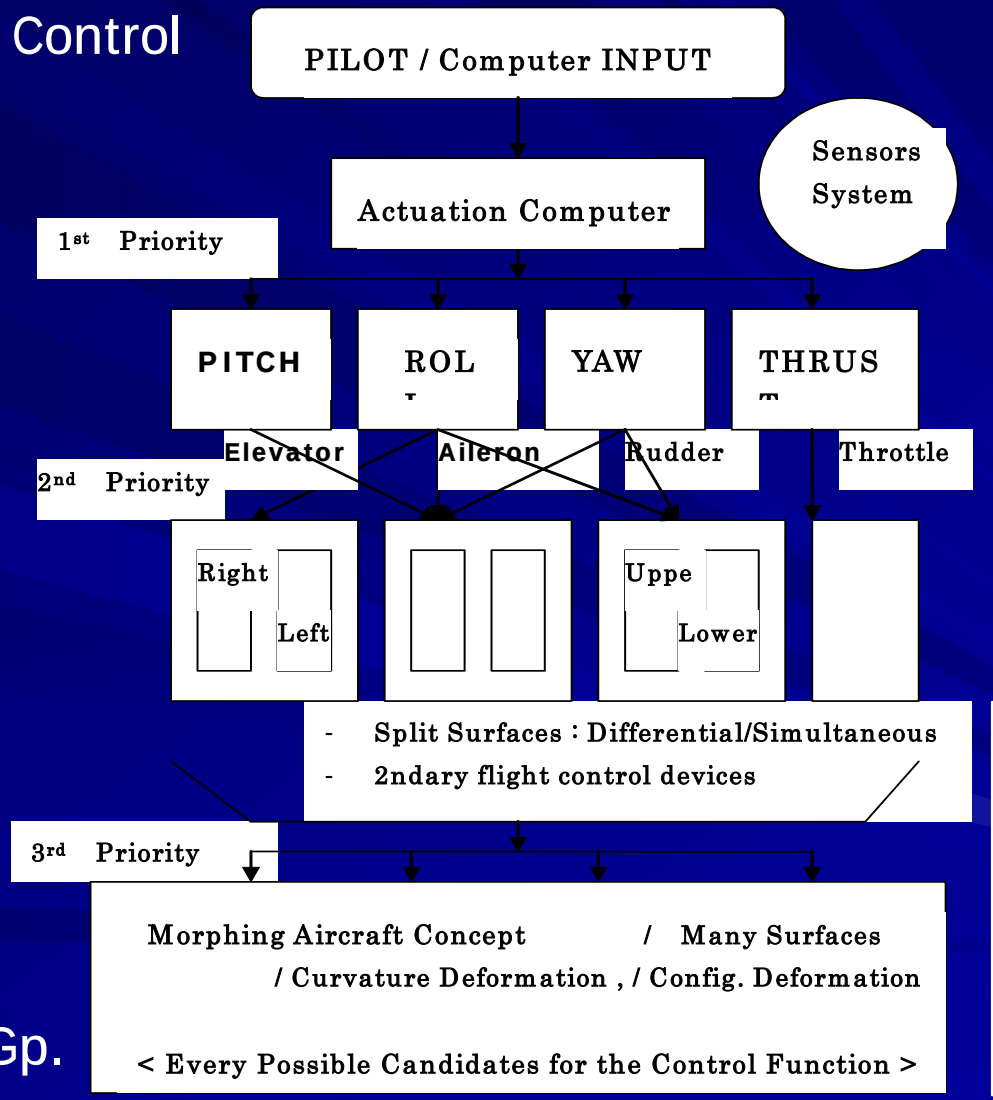
- Dispersed Arranged, with Simplex Actuators
  - Many Control Surfaces / Actuation Points
  - Elastic Structure / Morphing Aircraft
- Grouped Effectors Control each of 3 Axis



Flexible Actuation System

- in Basic Layer Control

- Many Alternatives
  - Control Surfaces,
  - Curvature Bending
- Independent Actuation
  - for each surface
- Functionary Assigned Control Group
  - for Pitch/Roll/Yaw Gp.



Reflex Action Type of Reconfiguration Control in Basic Layer

- **Step 1 : Reflex Action**

  - for distinct faults

  corrective action by all of active surfaces

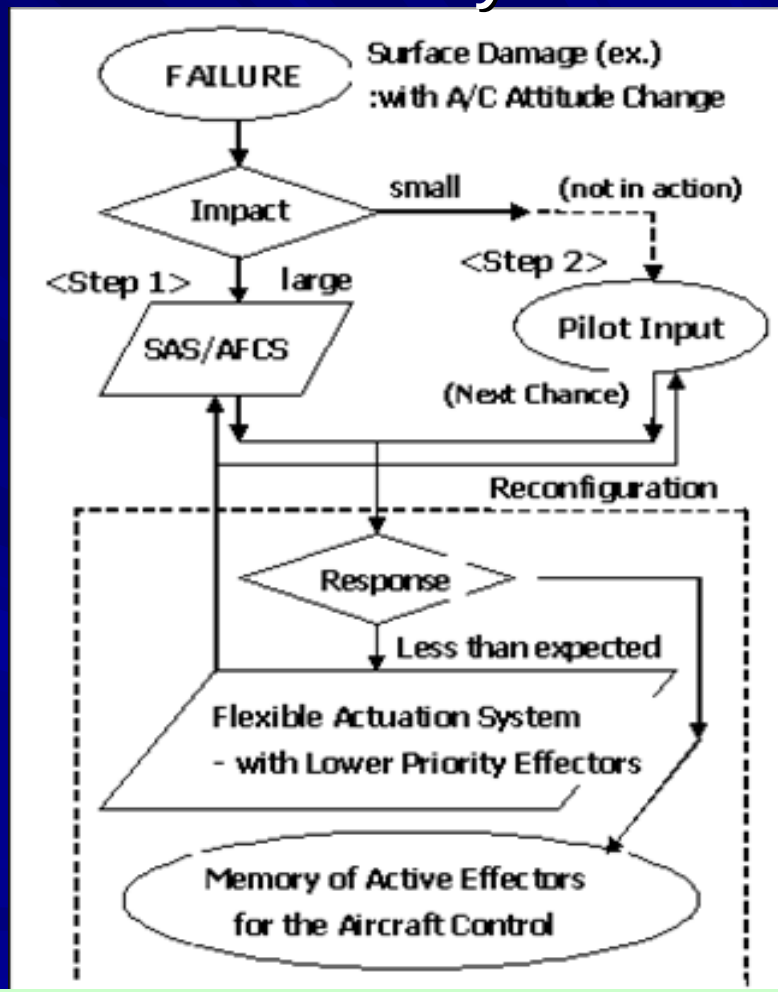
  <no pilot participation>

- **Step 2 : Pilot Control Initiative**

  - for dormant faults

  <pilot control finds faults, and evokes corrective actions>

  corrective action thru all of active surfaces/effectors



<The acted effectors are in memory, & applied thereafter for the function>

Double Layered Reconfiguration Control -as Core Control Law for Fault Immune Sys.

- **Upper Layer**
  : Autonomous /Optimum Robust Control with Reconfiguration (current practice for control)
- **Basic Layer** / implicit FDI
  : Reflex Action Control for a failure with Flex. Act. Sys.

Hierarchy Structure for FCS

Autonomous	Flight Command System : Mission Control : Air Traffic Communicatn/Action : Flt Safety / Reconfiguratn

<Conventional Control Hierarchy>

Automation*	Flt Managemt System AFCS
Improvement (for the system characteristics)	SAS / CAS / Active Control Tech.
Sys.Operation*	Basic FCS

Safety	Reflex Control :Reconfiguration with Flex. Actuation (as inherent function)

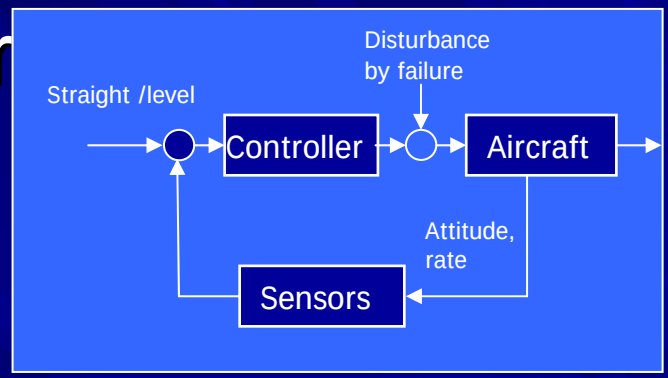
* : Conscious Control Level

Fig. 10 Flight Control Hierarchy

(Math) Simulation Results -1 (1)

for Basic Layer Control

- Attitude/Alt. Hold Controller
  : disturbance control,
  with “trim” reference



:

δ_a ⇒ If $\delta_a = \delta_{a,authority}$,or $\frac{\partial \delta_a}{\partial t} = 0$ Then $K\delta_r = \delta_a$ ⇒ If $\delta_r = \delta_{r,authority}$,or $\frac{\partial \delta_r}{\partial t} = 0$ Then $K\delta_{e,differential} = \delta_a$ ⇒

:For Controller

(ex.)

Add, and $\frac{\partial p}{\partial t} \le k(const.)$ (if necessary)

Used Actuator are in memories, with the amount

And applied thereafter, in the proportion

(Math) Simulation Results -1 (2)

for Basic Layer Control

- Altitude Recovery
  - by stabilator

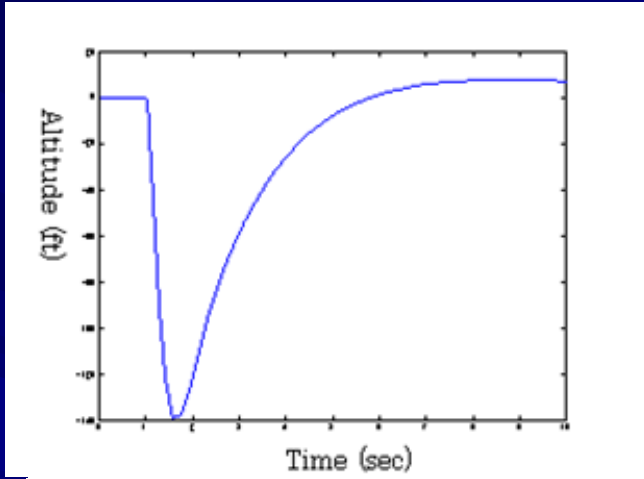
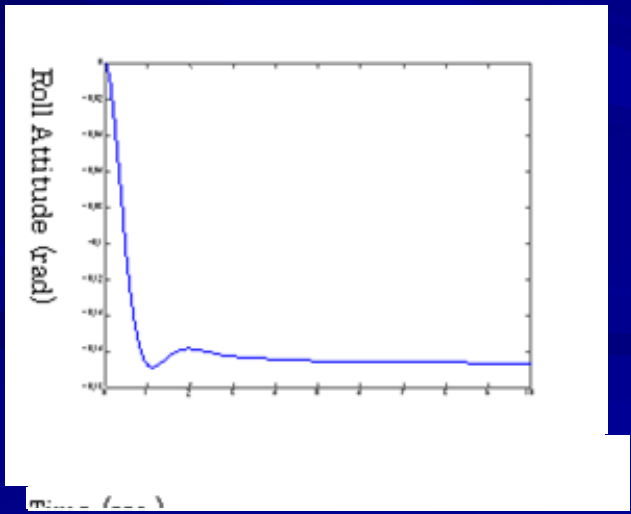


Fig. 5 Altitude Recovery by Stabilator

The alternatives have the capability !!

We should design the A/C, so that the alternative could have enough capability.

- Attitude Control for 'Roll'
  - by rudder



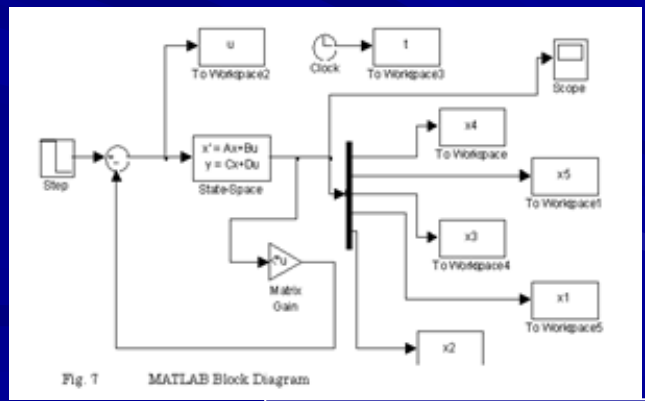


Fig. 7 MATLAB Block Diagram

Applying MATLAB

(Math) Simulation Results -2

by Flight Simulator

- **Test 1** : Step 1 / no peculiar feeling

  - Monitor the simulated failure and recovery condition by the alternatives < with 0.5 sec time lag>

- **Test 2** : Pilot Control / maneuverable

  - Input to the control by the alternatives

Pilot Control → Aircraft with Alternative Control Surfaces

→ **Reflex Control is under Right way**

Fig. 8 NIT Flight

Total sequence tests are req'd

Upper Layered Autonomous Control

- **Autonomous Control**

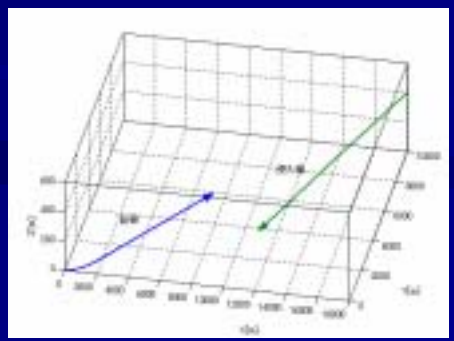
  ; situation judge

  - collision avoidance
  - flight path generation
  - reconfiguration control

- **Communication with ATC**

  <Fuzzy Expert Control>

  @ former ICAS meeting



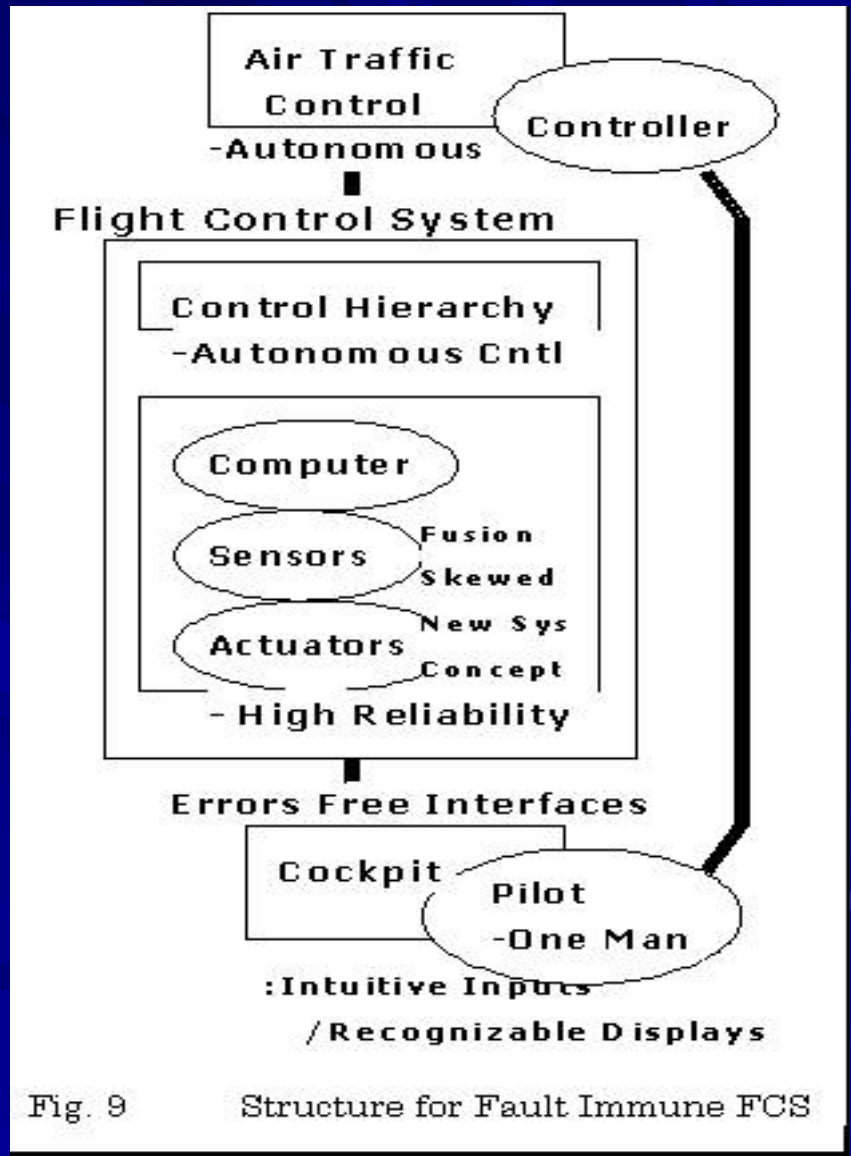
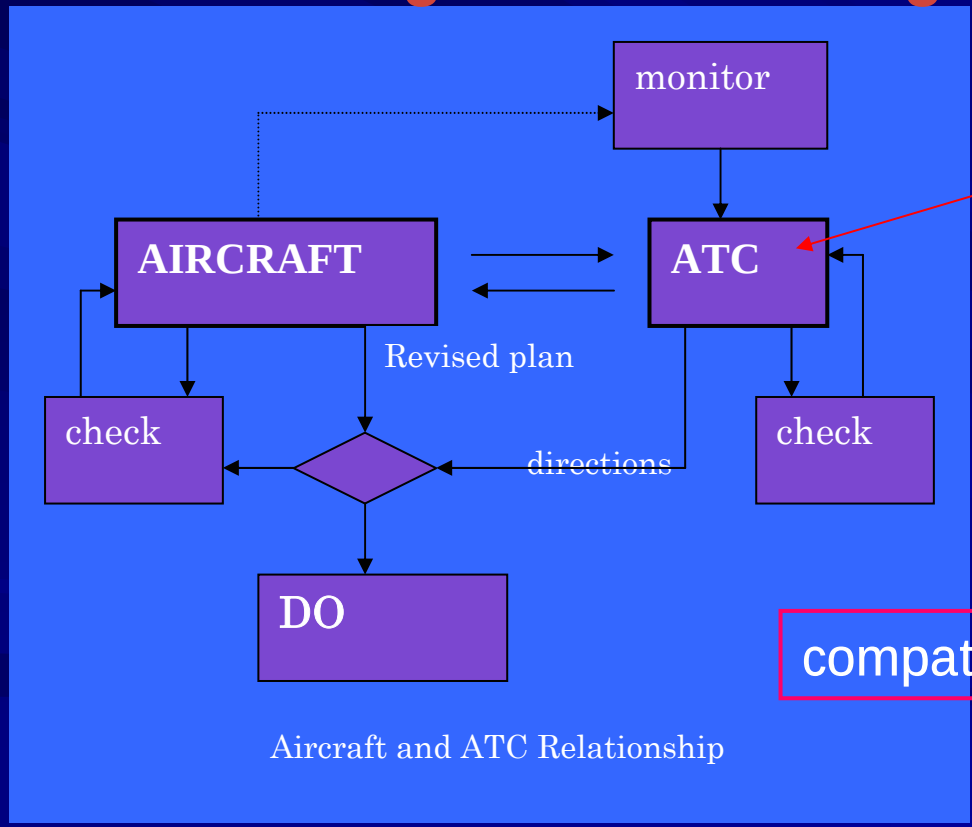


Fig. 9 Structure for Fault Immune FCS

Fuzzy Expert Control - 1st Step (2)

- Flight and Mission Organizing : Prior to Action

<while following the current flight plan>



Aircraft and ATC Relationship

(Autonomously)

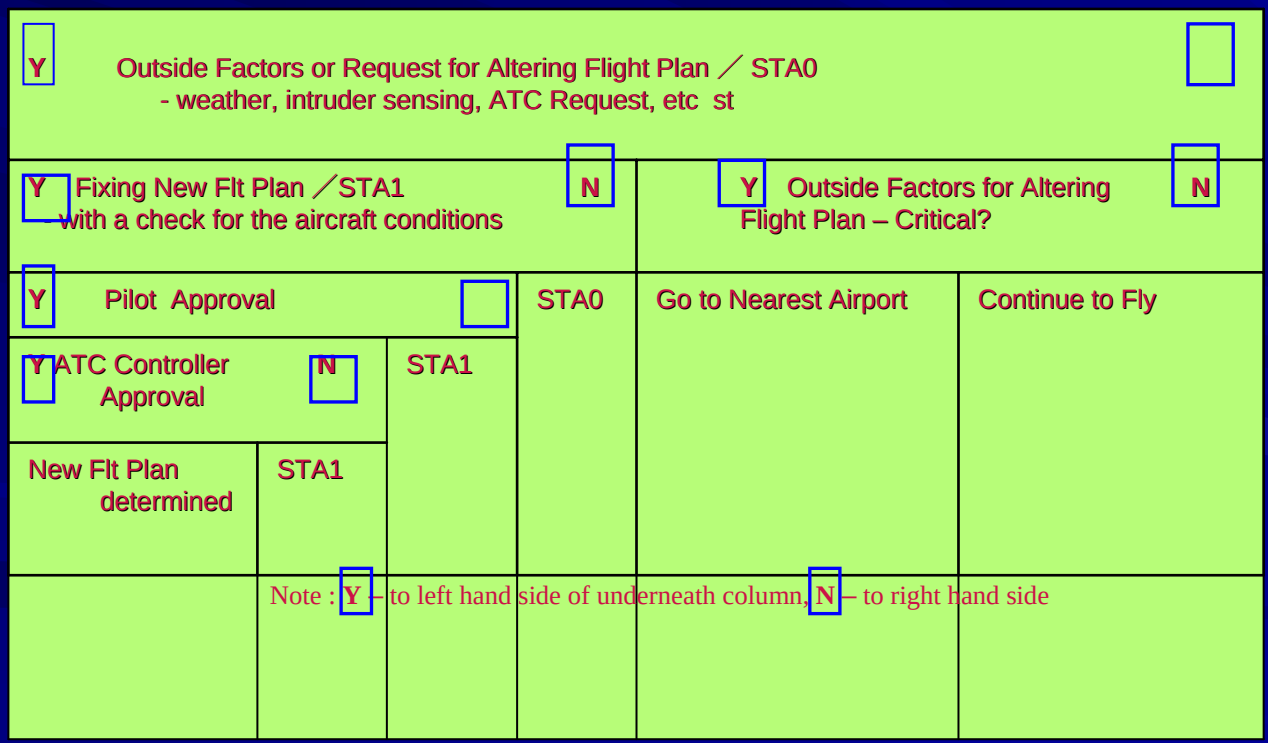
Digital Communication :Expert System

compatible ATC are req'd

Fuzzy Expert Control - 1st Step (1)

- Step 1 : Decision Making Phase

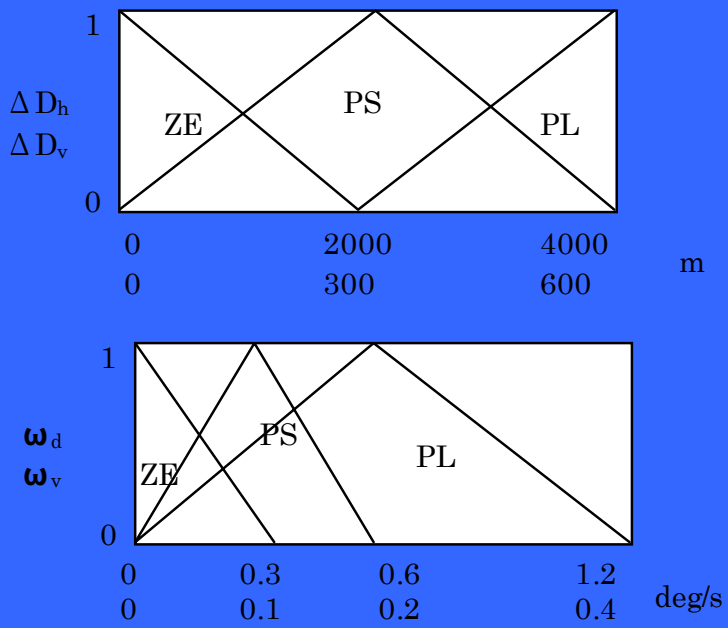
Traffic Control - Flight Plan Change ; Chapin Chart



Expert System :Sequence Control

Fuzzy Expert Control –Math Simulation

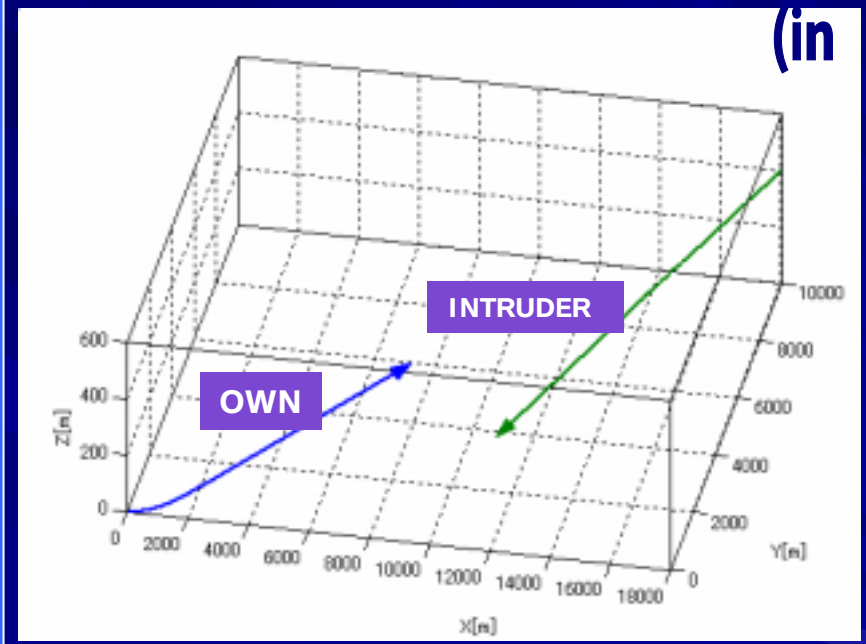
Membership Function



Fuzzy Rule

ω_d		$\Delta D_h, \Delta D_v$		
ω_v		ZE	PS	PL
T_h	ZE	ZE	PL	PL
T_v	PS	ZE	PS	PL
	PL	ZE	PS	PS

EX. Collision Avoidance (in 3D)



This is also achieved thru the actuation of the alternatives for the reconfiguration..

Human and Autonomous Control in System

/Pilot Interface

- Unconscious Controls for Human

  -Brain Control by Cerebral/Cerebellum
  <normal control route>

  -Reflex Control by Spinal Code :Actions for Safety

  -Autonomic Nerve : Life Support

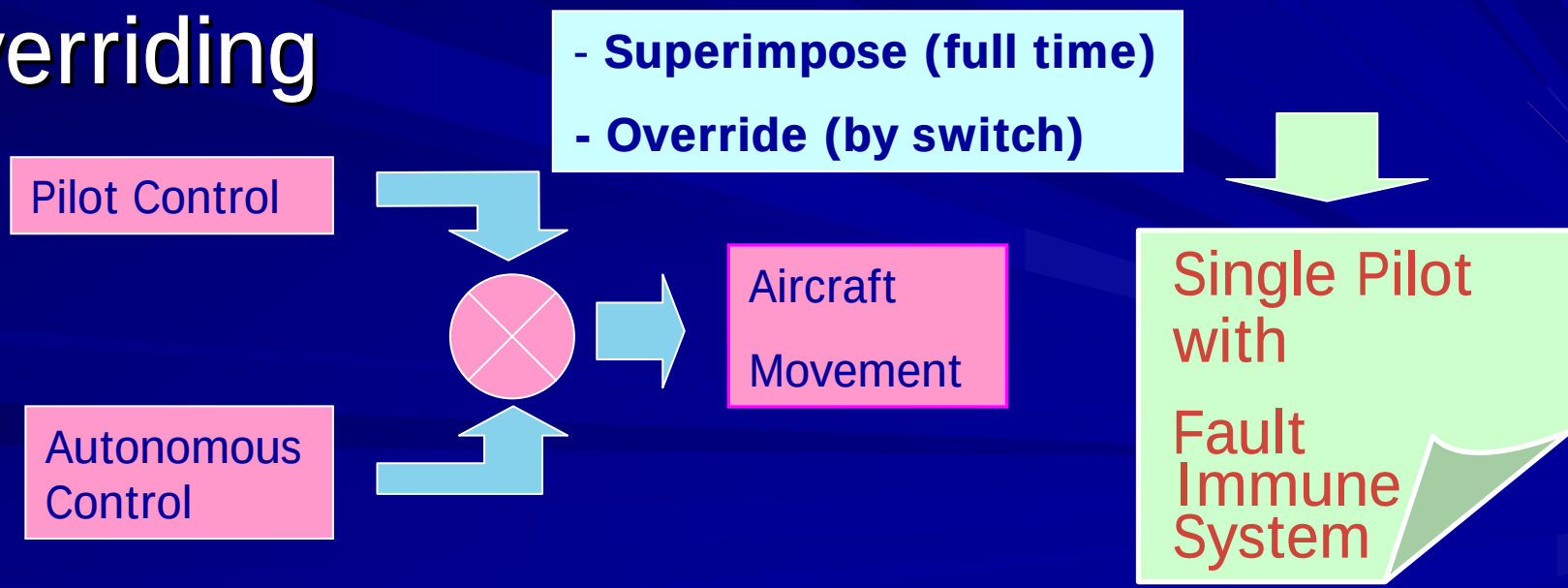
Information in Unconscious Activities, in Human Behavior, are said

10^5 times as many as in Conscious One.

Pilot could adapt to the System of More Automation by Autonomous Control

Pilot Controls in Autonomous System
<Commander & Full Time Participation>

- Superimposing
  - for tailoring the control to the feeling of the pilot
- Overriding



Conclusions

- Double Layered Reconfiguration Control with reflex action layer and with usual autonomous control layer, is presented as an effective control law concept for the Fault Immune Aircraft.

- Fault Immune System, which is based on the reconfiguration in need, and the 10^{-12} of the ultra high reliability system in the normal operation, is offered with the single pilot operation, as a near term trend.

General Discussion on Fault Immune Flt. Con. System -3

- Systems
  - Sensors
  - Actuators
  - Computers
  - Data Bus
  - Other

10^{-12} Failure/ Hour

for a critical failure

<Fault Tolerant Design>

- Control Laws ; <More Autonomous> Fault Immune thru Reconfiguration
- Pilot Interface ; Intuitive Inputs & Recognitions

Proposal for FAR Part 25

- For a Critical Failure :

  to interpret “extremely Improbable”

  as “ 10^{-12} ”

  (Article 25.1309, and the related)

- And which is attainable.

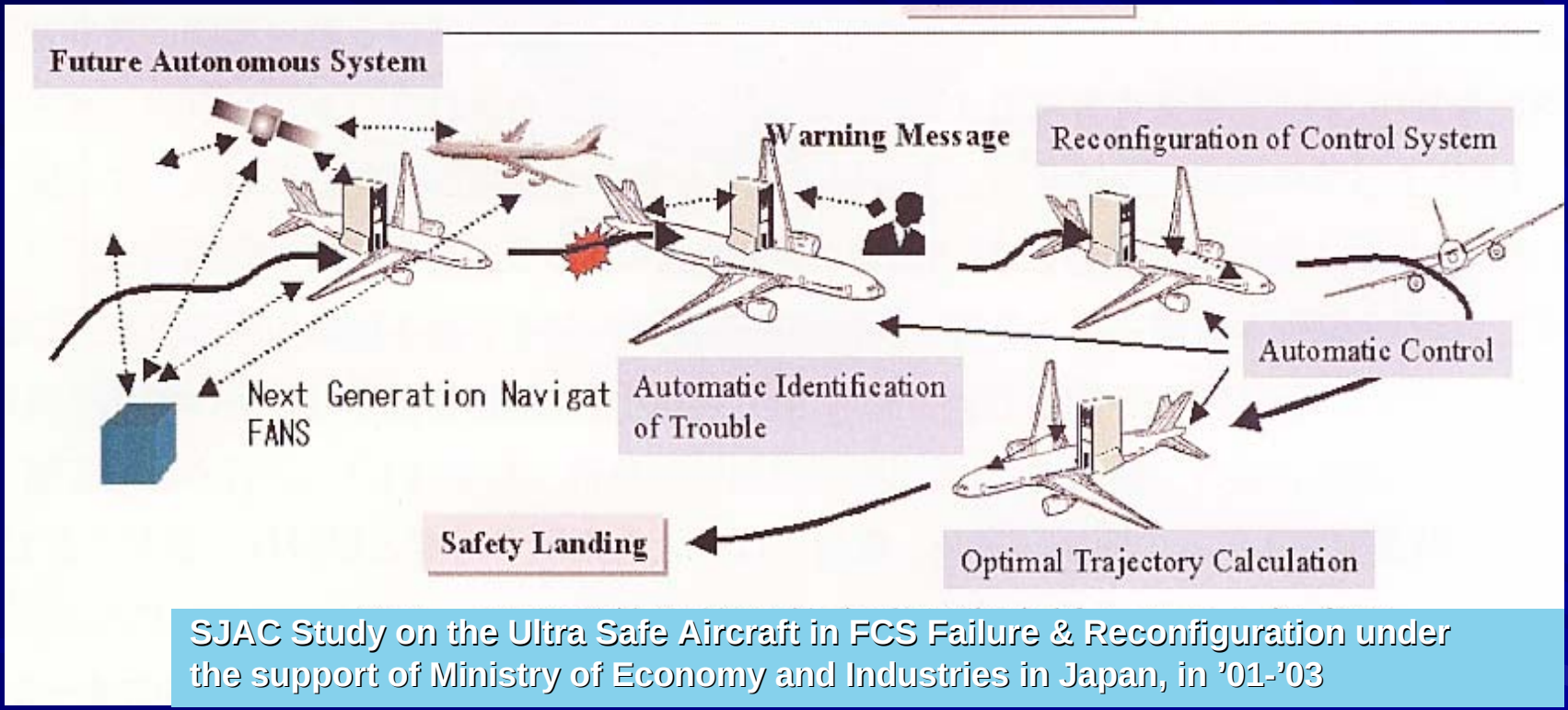
Concept for Reconfiguration Control

- The aircraft should be able to continue the flight in any conditions, thru the reconfiguration of the normal laws, even in the abnormal conditions.
  (like birds, or insects)

- Reconfiguration in Layered Control (proposed)
  as a core control law for the fault immune aircraft
  - Human reacts to endangered happenings in a reflex manner. (; Basic Layer Control)
  - As a next step, the human considers optimal ways of doing in what to do next. (; Upper Layer Control)

Appendix:

SJAC Study on Fault Tolerant FCS -1



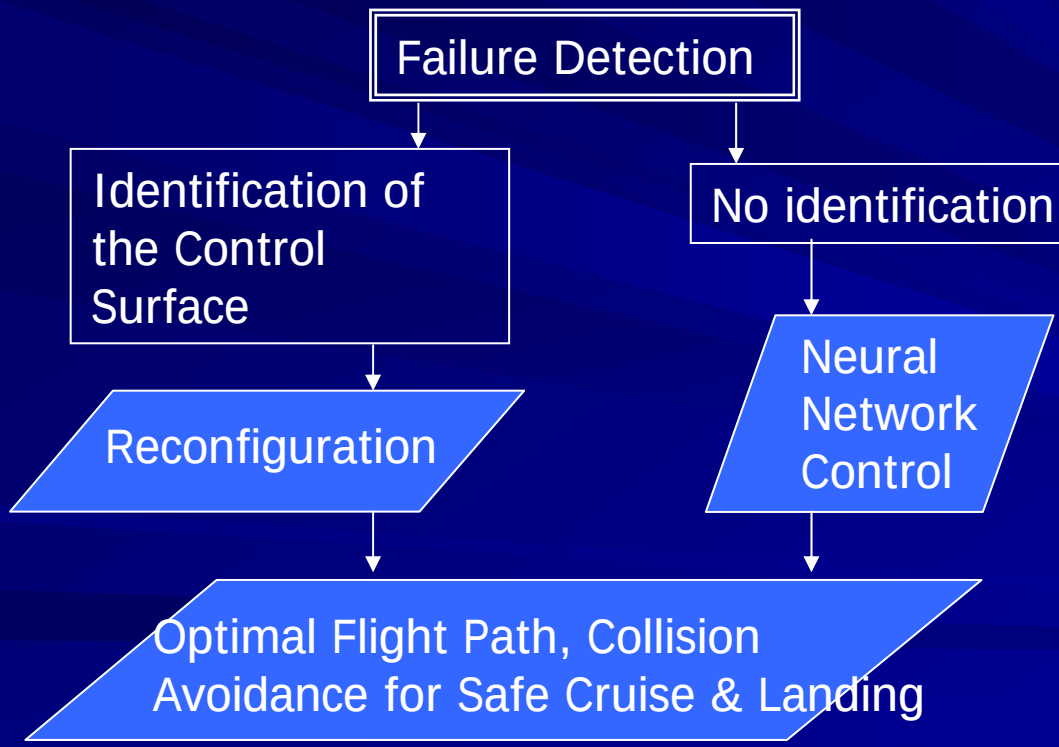
SJAC Study on the Ultra Safe Aircraft in FCS Failure & Reconfiguration under the support of Ministry of Economy and Industries in Japan, in '01-'03

The Consideration both for Normal and Abnormal State are important.

Appendix:

SJAC Study on Fault Tolerant FCS -2

- SJAC Study (for 2002~2003, 2005~2007) on Fault Tolerant Flight Control System



Simulation Study & Flight Test

By collaboration of
- Tokyo University
- A/C Makers
- Institute

Appendix Computers

Computer Architecture for Flight Control System

<Clear-cut Hierarchy in function and hardware>

- Flight Control

  : Flt Cmd Sys. , FMS, Auto-Pilot, etc.

- Flight Safety Control

  : SAS, CAS

  : Actuation Control

  : Active Control Technology, etc.

- System Sustain Control

  : Basic Flight Control System,

  : Electric & Electronics Sys., Hydraulic Sys., Cockpit Sys., etc.

Appendix Flight Command System

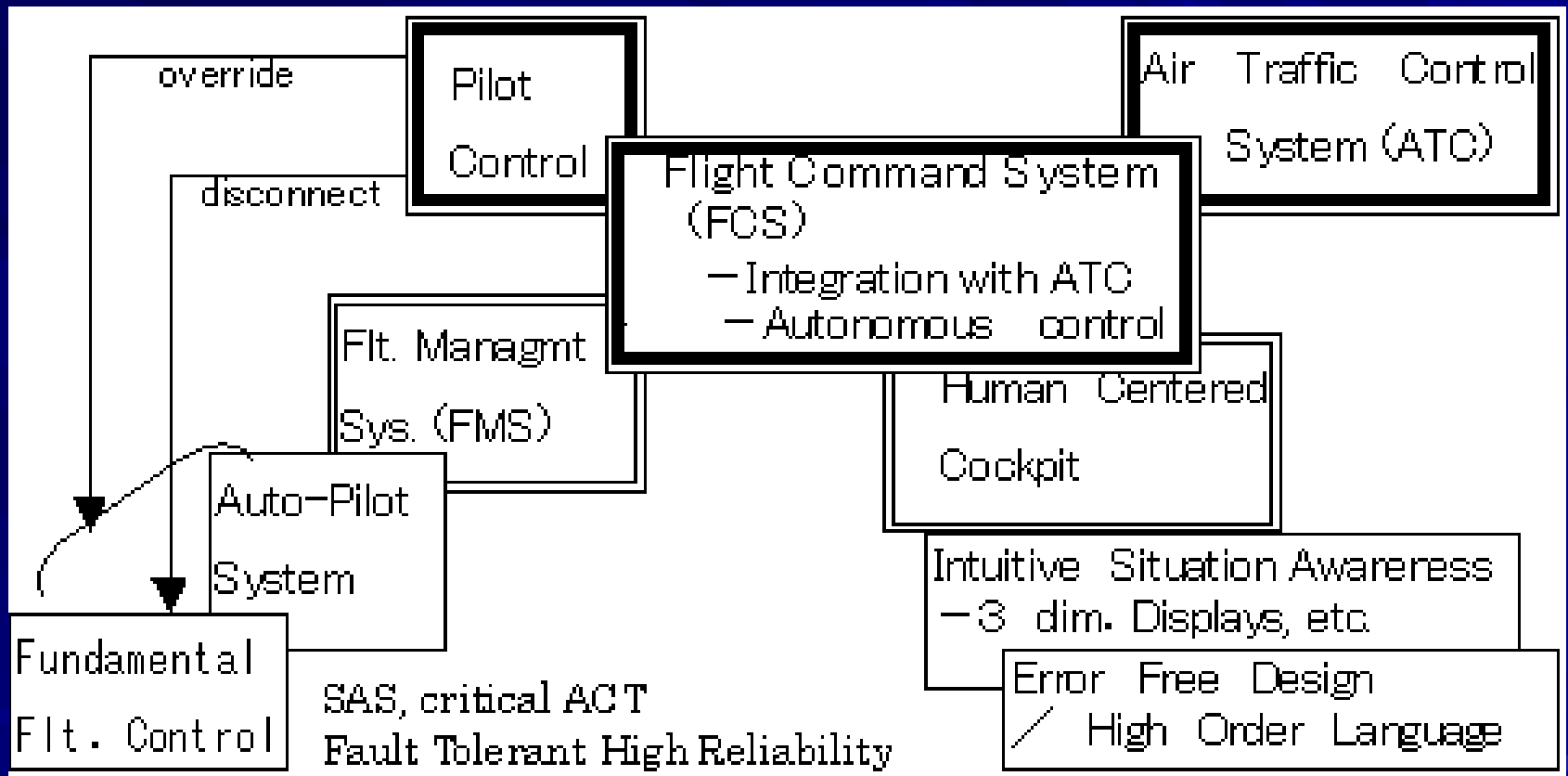


Figure 1. The Concept of Flight Command System

Reflex Type of Reconfiguration

- Function for FDI in normal reconfiguration control / Step 1
  - thru Reflex Action + Flexible Actuation

- And Preliminary Action / Step 1 & 2
  - to stabilize the aircraft, or control by the active effectors

Flex. Act. Sys. ; Search for Active Effectors, And Make them work as much as possible
- Multi-success Path Design is Required.

Appendix:
Concept for Reflex Reconfiguration

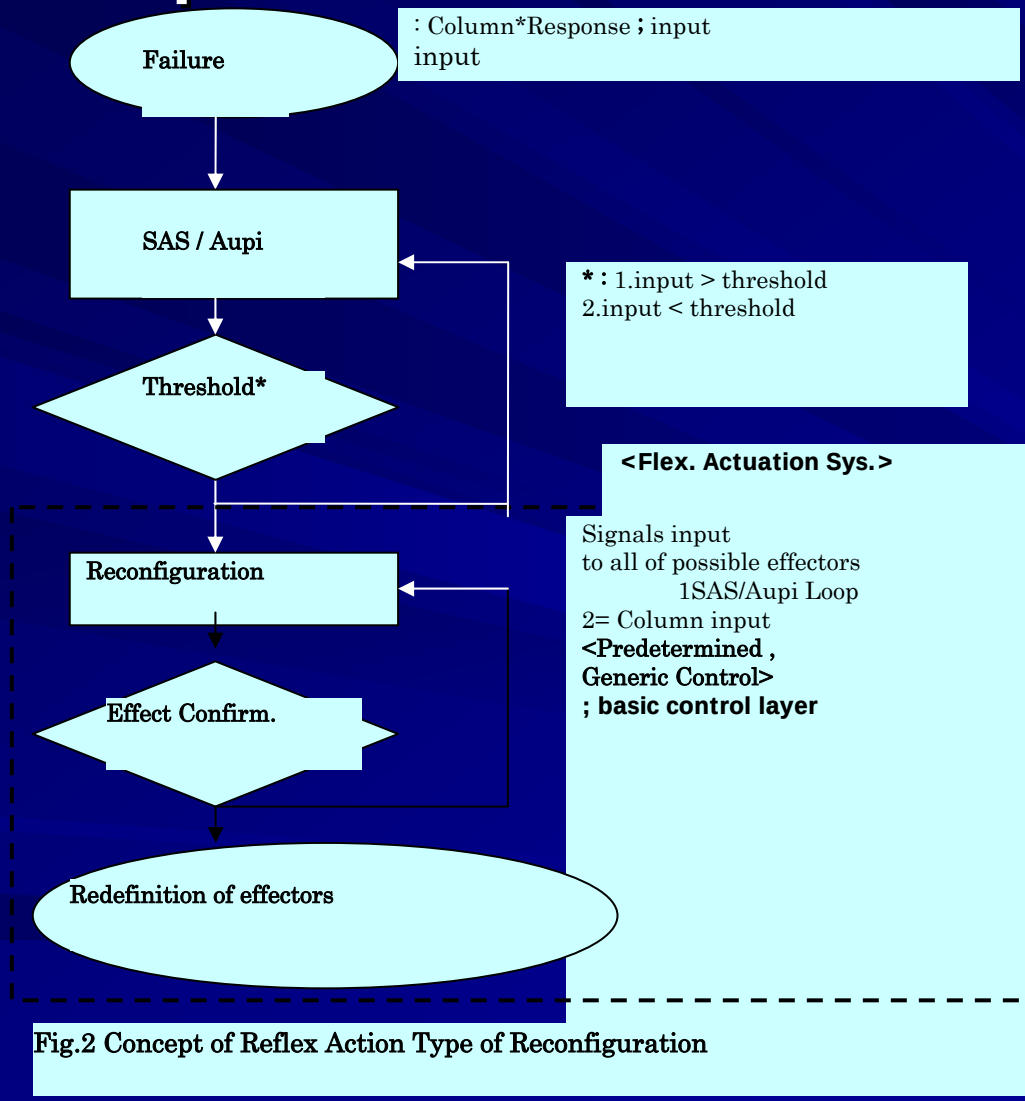


Fig.2 Concept of Reflex Action Type of Reconfiguration

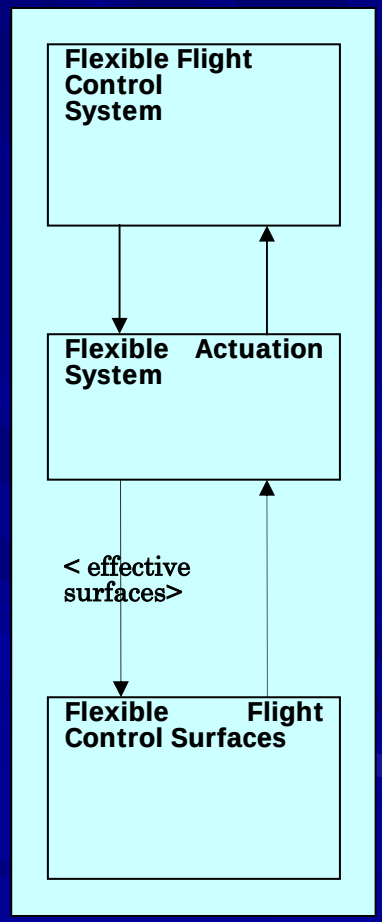


Fig.1 Flex.FCS

Flight Control Actuation System

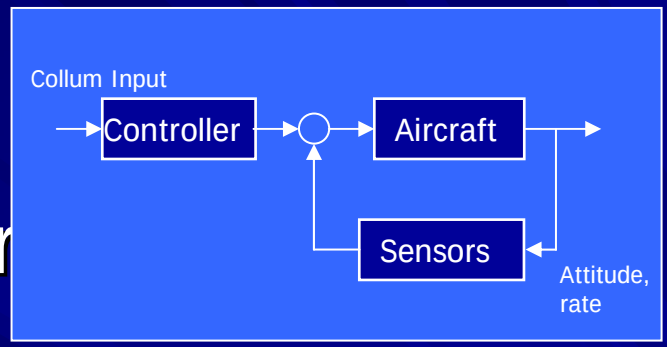
- Operation Mode Concept / Reflex Action
  : Attitude Hold Mode (for Disturbance)
  : Control Input Compensation Mode
  (for Pilot Input)
  - Actuators by the unit of Control Group

(Ex.) the longitudinal actuation group ,
for the case of Elevator Failure

The Actuated are in memory, used thereafter

Flight Control Actuation System

For Step 2 /Test 2



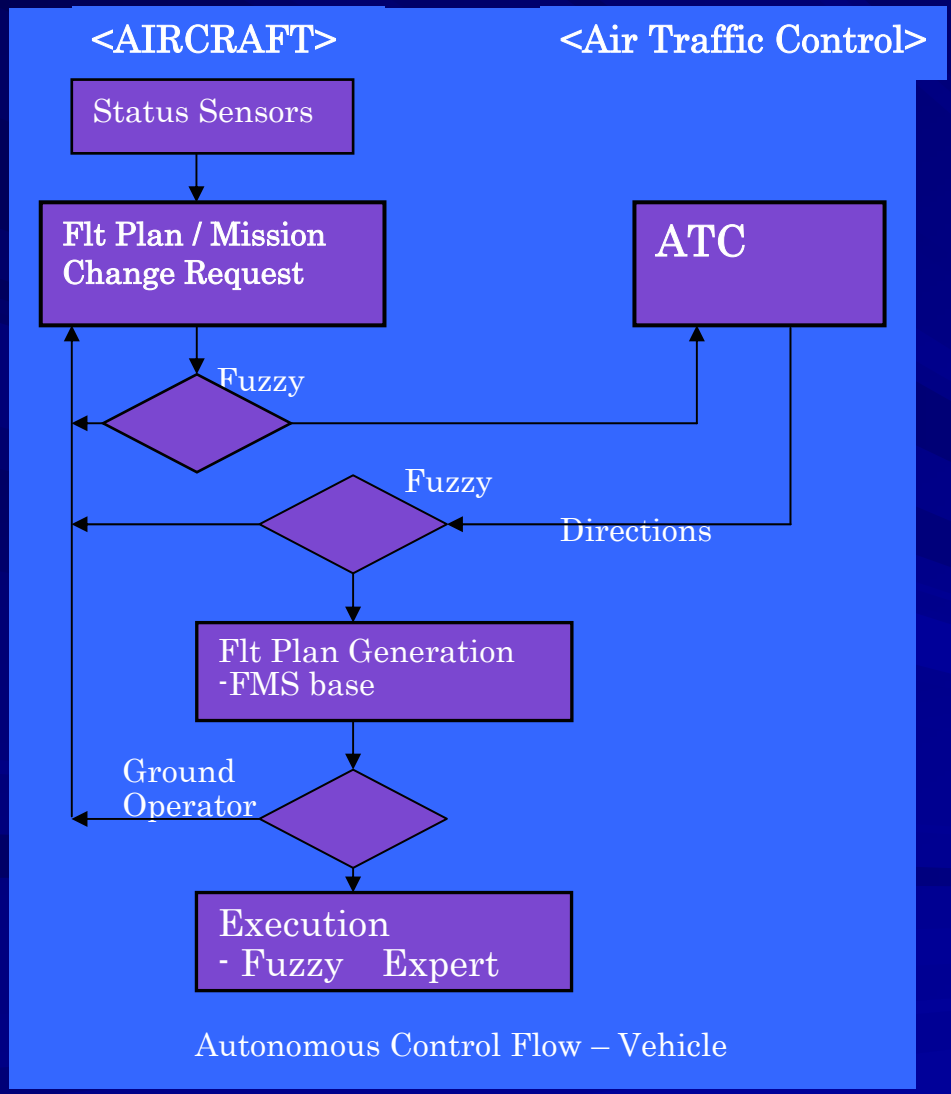
- Control Input Compensation Controller
  - : CAS Control law with a reference by column input
  - : same logic as a previous page

δ_a ⇒ If $\delta_a = \delta_{a,authority}$,or $\frac{\partial \delta_a}{\partial t} = 0$ Then $K\delta_r = \delta_a$ ⇒ If $\delta_r = \delta_{r,authority}$,or $\frac{\partial \delta_r}{\partial t} = 0$ Then $K\delta_{e,differential} = \delta_a$

Add ; and condition of $\frac{\partial p}{\partial t} \le k(const.)$

Fuzzy Expert Control - 2nd Step (2)

- Transient Action to New Mission/Plan



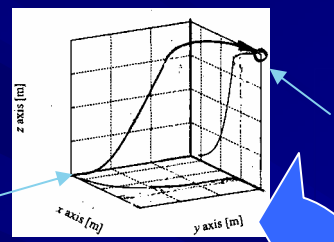
; Transient Action in between FMS Operations

/ Transfer to a Flight Plan Re-starting point

Fuzzy Expert Control
- Flight Pattern Generation in More Automation

- Basic flight performer
  :FMS
  <from Take Off to Landing >
- ATC interaction
  :Autonomous Control
  by Fuzzy-Expert Control

such as for
intruder avoidance,
adverse area avoidance,
mission change,
landing sequence, etc.

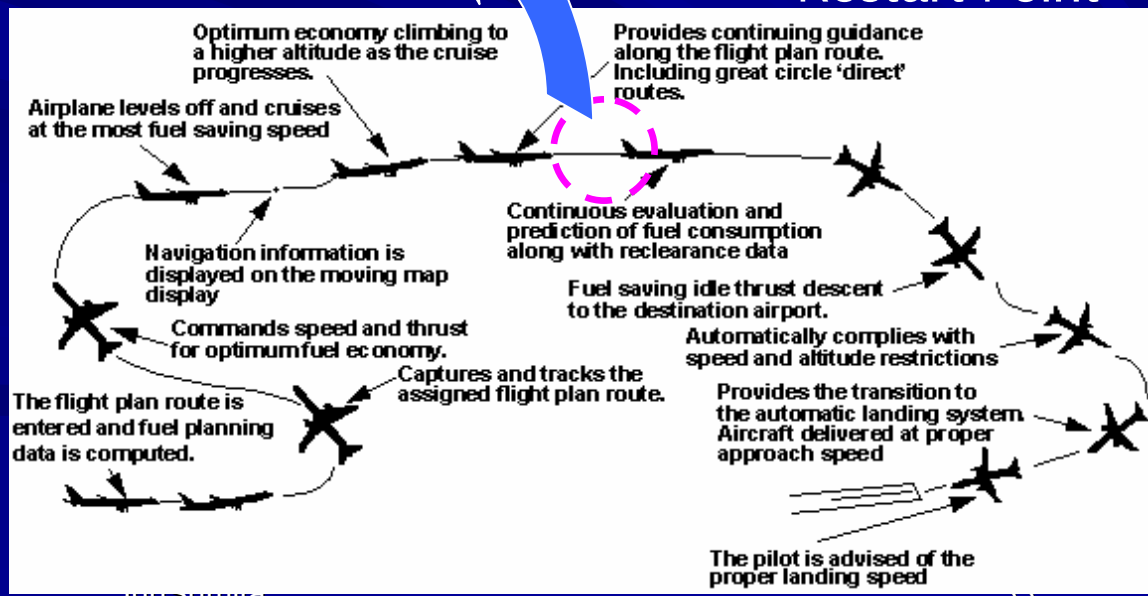


Change

Fuzzy Control Step

1st: Decision for
Plan Change

2nd: Action to FMS
Restart Point



Fuzzy Expert Control - 1st Step (3)

- Go / No Go Decision : Cost Function > Threshold

Example ; $\sum [If - Conditions \times \Pr iority]$

IF – Conditions:

- Collision Possibility : (ex.) 1/(distance-20nm)

From all information sources

- ATC Request : Priority, or Emergency Level

- Aircraft Request : Priority, or Emergency Level

due to Accident, Failure,

Bad Weather, etc.

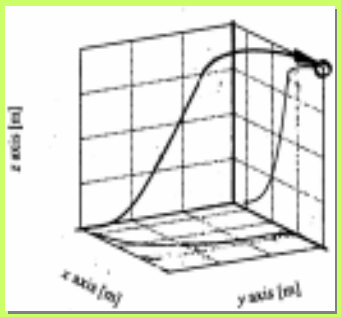
Priority/Fuzziness/Emergency Level:

Fuzzy Expert Control - 2nd Step (1)

- Step 2 : Action Phase to execute the change

  - membership functions
    ; distance
    ; deviation etc.

  turning rate,
  with appropriate
  Fuzzy Rules

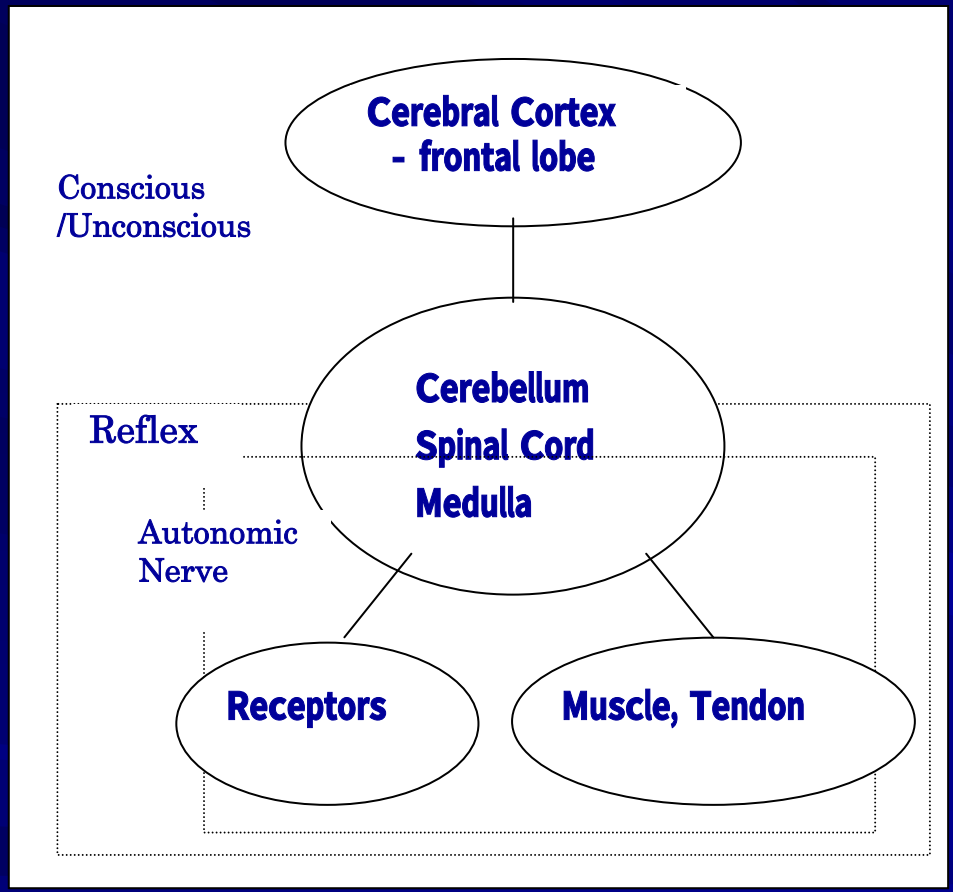


; Goal
(FMS restart)

Start to
Change

Figure 4. Step 2 Concept

Human Brain Control in Layered



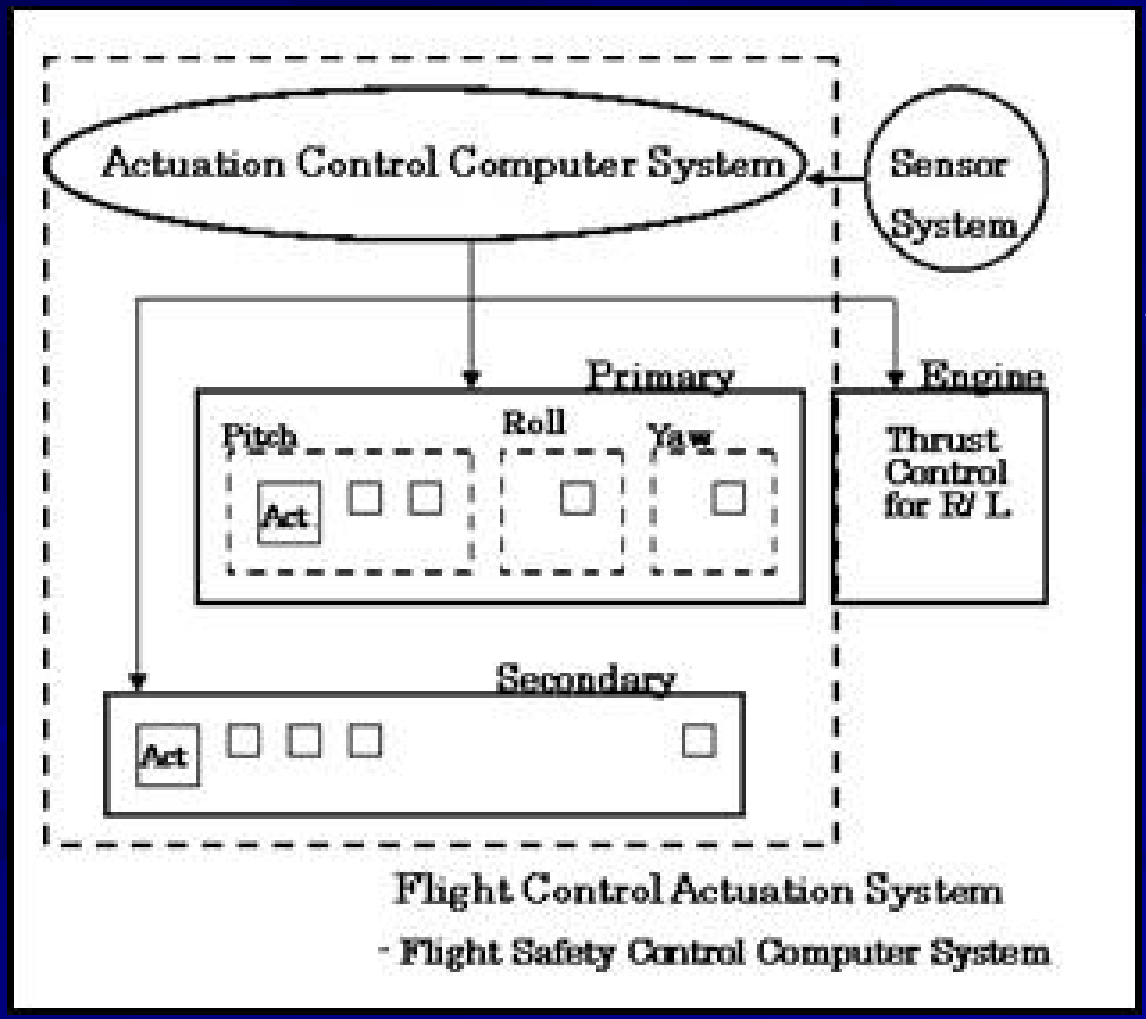
Appendix **Flexible Actuation System**

- Dispersed Arranged, with Simplex Act.
  - Elastic Structure / Morphin Aircraft
  - Many Control Surfaces / Actuation Points
- Grouped Effectors Control for 3 Axis

- Smart EMA/EHA
- Piezo-Actuator

$(10^{-5})^3 = \underline{\mathbf{10^{-15}}}$

Appendix Flight Control Actuation System - in Flt. Cont. Safety Computer Sys.



- **Reflex type of Action to Aircraft Failure**
- **Operation by Actuation Group for Control**
  (includ. for Normal Operation)
  - **Longitudinal Control**
    : Elevators, Stabilator, Spoilers, Thrust,
  - **Lateral Control**
    : Aileron, Rudder, Spoilers, Differential Elevators,
  - **Directional Control**
    : Rudders, Aileron, Differential Thrust,

Appendix Ex. for Deflection Control

<Deflection Control>

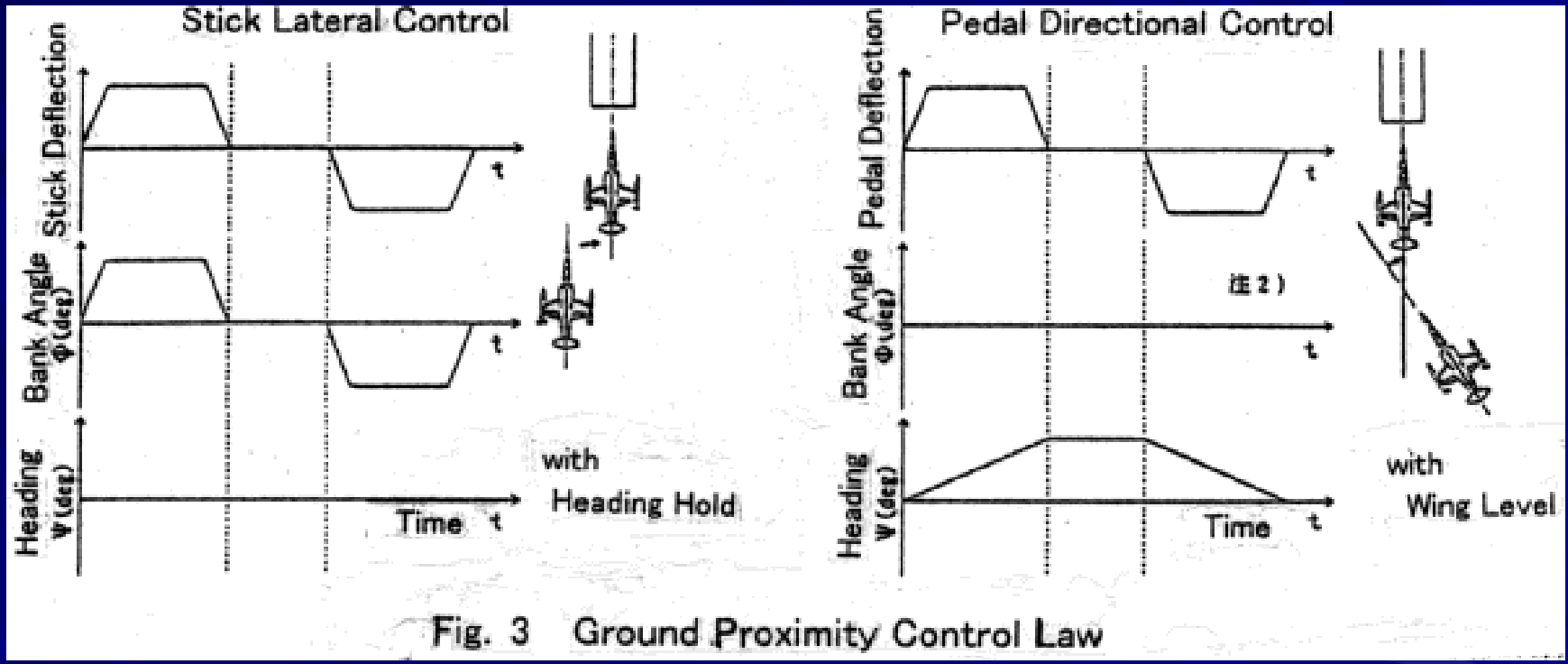


Fig. 3 Ground Proximity Control Law

<Flight Path Control>