ADAPTIVE PASSIFICATION-BASED FAULT-TOLERANT FLIGHT CONTROL

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CNRS-RAS cooperative research project “Robust and adaptive control of complex systems: Theory and applications”
The adaptive passification-based method is used for fault-tolerant flight control design. Simulation results for HL-20 model and results of experiments with the “LAAS Helicopter Benchmark” are presented, showing efficiency and fault-tolerance of the proposed method.
OUTLINE

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2. Passification method and adaptive controllers with Implicit Reference Model

LTI SISO system

\[ A(p)y(t) = B(p)u(t), \quad t \geq 0, \quad (1) \]

-Scalar control signal, \( y \) – controlled output;

\[ A(p) = p^n + a_{n-1} p^{n-1} + \cdots + a_0 \]

\[ B(p) = b_m p^m + b_{m-1} p^{m-1} + \cdots + b_0 \]

-Uncertain polynomials on \( p = d/dt \).

Plant model parameters are unknown.

Control problem:

tracking the reference (command) signal \( y_{\text{ref}}(t) \).
Implicit Reference Model (IRM)

Introduce $\sigma(t) = G(p)y(t) - D(p)y_{\text{ref}}(t)$ - the adaptation error signal,

$$G(p) = p^l + g_{l-1}p^{l-1} + \cdots + g_0, \quad D(p) = d_r p^r + d_{r-1} p^{r-1} + \cdots + d_0$$

given polynomials, specifying desired properties of the closed-loop system; $G(\lambda)$ - stable (Hurwitz) polynomial.

The signal $\sigma(t)$ – the equation error for the equation

$$G(p)y_*(t) = D(p)y_{\text{ref}}(t), \quad (2)$$

$\sigma(t) \equiv 0 \implies$ controlled variable $y(t)$ satisfies (2).

Hence (2) represents reference model implicitly; it is called the Implicit Reference Model (IRM).
Adjustable control law

Adjustable control law in the *main loop*:

\[ u(t) = k_r(t)D(p)y_{ref}(t) + \sum_{i=0}^{l} k_i(t)(p^i y(t)), \]

\( k_r(t), \quad k_i(t), \quad (i = 0, 1, \ldots, l) \) - tunable parameters
Adaptation algorithm

The passification based design method leads to the following adaptation algorithm:

\[
\dot{k}_r(t) = \gamma \sigma(t) D(p) y_{ref}(t) - \alpha(k_r(t) - k_r^0), \quad k_r(0) = k_r^0, \quad (4a)
\]

\[
\dot{k}_i(t) = -\gamma \sigma(t) p^i y(t) - \alpha(k_i(t) - k_i^0), \quad k_i(0) = k_i^0, \quad (4b)
\]

\[
\gamma > 0 - \text{adaptation gain;}
\]

\[
\alpha \geq 0 - \text{parametric feedback gain;}
\]

\[k_r^0, k_i^0 - \text{prior estimates of the appropriate values of the tunable parameters, } i = 0, 1, \ldots, l.\]
Applicability conditions – Passification Theorem

The adaptive controller (3), (4) applicability conditions (Passification Theorem; Fradkov, 1974):

1. \( B(\lambda) \) is Hurwitz polynomial,
2. \( l = k - 1 \); where \( k = n - m \) - plant (1) relative degree.

The degree of \( D(p) \) is bounded by the amount of available derivatives of \( y_{ref}(t) \) and is subjected to designer’s decision. A matching condition (used for the Model Reference Systems) is not necessary for IRM adaptive controllers. The order of reference equation (2) is equal to \( l \) and can be significantly less than the plant model order \( n \).
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[ Matlab/Simulink Aerospace Blockset demo aeroblk_HL20.mdl ]
IRM adaptive controller for HL-20 angle of attack

\[ u(t) = k_I(t) \int_0^t e(t) \, dt + k_\alpha(t)e(t) - k_q(t)q(t). \]

\( \alpha \) - angle of attack, \( q \) - pitch rate, \( e = \alpha_{ref} - \alpha \) - reference error

\[
\begin{align*}
\dot{k}_I &= -\gamma_I \sigma_t \int_0^t e(t) \, dt + \lambda(k_I^0 - k_I(t)), \\
\dot{k}_\alpha &= -\gamma_\alpha \sigma_t e(t) + \lambda(k_\alpha^0 - k_\alpha(t)), \\
\dot{k}_q &= \gamma_q \sigma_t q(t) + \lambda(k_q^0 - k_q(t)), \\
\sigma_t &= g_I \int_0^t e(t) \, dt + e(t) - g_q q(t)
\end{align*}
\]
Simulation results for HL-20 flight control (nominal case)

Fig. 1. Tracking the reference signal. $H_\infty$ controller (2-D scheduling). Nominal case.

Fig. 2. Tracking the reference signal. Adaptive controller. Nominal case.
Simulation results for HL-20 (actuator fault to 45%)

Fig. 4. Tracking the reference signal. $H_{\infty}$ controller (2-D scheduling).

Fig. 5. Tracking the reference signal. Adaptive controller.
Simulation results for HL-20. Controller gains time histories

Nominal case

Actuator effectiveness falls down to 45% from the nominal at $t_\star = 30 \text{ s}$
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*Quanser/LAAS “Helicopter” benchmark*
Nomenclature

angles of: 
θ – pitch, 
λ – travel, 
ε – elevation.

\[ u_f, u_b - \text{motor voltages}; \]
\[ \nu_x, \nu_z - \text{control signals}; \]
\[ u_f = 0.5(\nu_z + \nu_x), \]
\[ u_b = 0.5(\nu_z - \nu_x). \]
**IRM adaptive PID-controller for ‘Helicopter’ pitch angle**

\[
u(t) = k_P(t)\bar{e} + k_I(t) \int_0^t \bar{e}(\tau) \, d\tau - k_D(t)\dot{\theta}(t)
\]

\[
e(t) = \theta^*(t) - \theta(t), \quad \bar{e}(t) = \text{sat}_E(e(t)), \quad \text{sat}_E(\cdot) \in [-E, E]
\]

\[
\dot{k}_P(t) = -\gamma_P \sigma_t \bar{e}(t) - \alpha_P(k_P(t) - k_P^0),
\]

\[
\dot{k}_I(t) = -\gamma_I \sigma_t \int_0^t \bar{e}(\tau) \, d\tau - \alpha_I(k_I(t) - k_I^0)
\]

\[
\dot{k}_D(t) = \gamma_D \sigma_t \dot{\theta}(t) - \alpha_D(k_D(t) - k_D^0),
\]

\[
\sigma_t = T \dot{\theta}(t) - \bar{e}(t)
\]
Experimental results

Fig. 8. Step responses of the pitch angle for system with the APID-IRM controller. Nominal case – solid line, 50% motor fault – dashed line, 100% motor fault – dotted line.

Fig. 9. Controller gains time histories; 50% motor fault.
Movie. Rear motor 100% fault
CONCLUSIONS

The adaptive passification-based method is used for fault-tolerant flight control design. An important advantage of the proposed adaptive control is simplicity of the design procedure compared to conventional model based design. Results of simulation for HL-20 model and experiments with the “LAAS Helicopter Benchmark” are presented, showing efficiency of the proposed method. It is demonstrated that the passification-based adaptive control approach leads to the rapid adaptive tuning algorithms, which makes it possible to use this method for actuator faults compensation.
Thank you!