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Finite-time-convergence Attitude Tracking Control for Rigid Spacecrafts Using Chebyshev ANN and Fast-NTSM Manifold

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REMARK: All three Authors have equally contributed to this paper, **Prof. Jing as the mentor** of now Dr. Shihong Gao, while *Professors Liu and Dimirovski acting as scientific advisors*. All correspondence please send to dimir@feit.ukim.edu.mk. Thank you.

0. PROLOG

- *Abstract*—The finite-time attitude tracking control for a rigid spacecraft subject to inertial uncertainties, external disturbances, actuator failures and saturation constraints is investigated using the ideas of:
- **Fast nonsingular terminal-sliding-mode manifold (FNTSM);** and
- **Unknown nonlinear function approximation with a Chebyshev artificial neural network (CANN).**
- **First the FNTSM is constructed, and then the unknown nonlinear function of sliding mode dynamics is approximated with a CANN.**
- A fault-tolerant attitude control law, which ensures that all the signals in the closed-loop system with spacecraft or orbiting satellite are uniformly ultimately bounded, is then designed by combining FNTSM and CANN techniques as appropriate.
- An improved control algorithm is derived to achieve finite-time attitude tracking. Extensive simulation experiments were conducted to verify the effectiveness of the proposed control scheme. A selected sample of those simulation results that demonstrate an outstanding control performance is given.

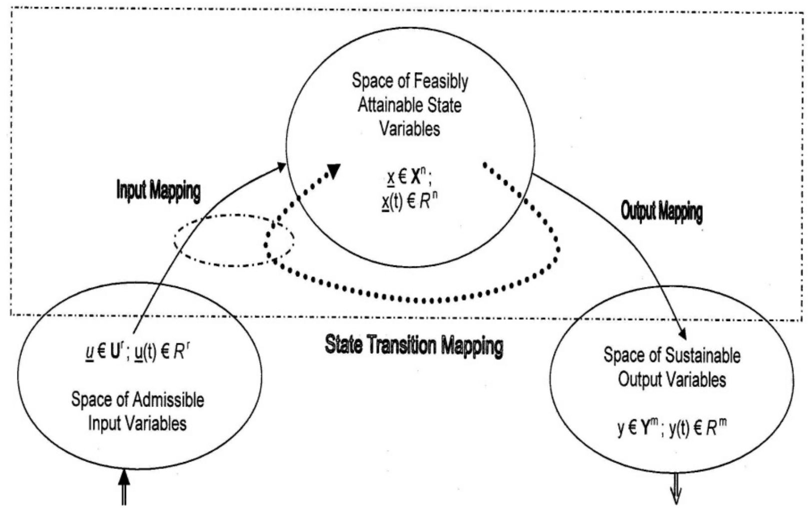


Fig. 1 An illustration of controlled general nonlinear systems in accordance to the Fundamental Laws of Physics (Dimirovski et al., **1977)**

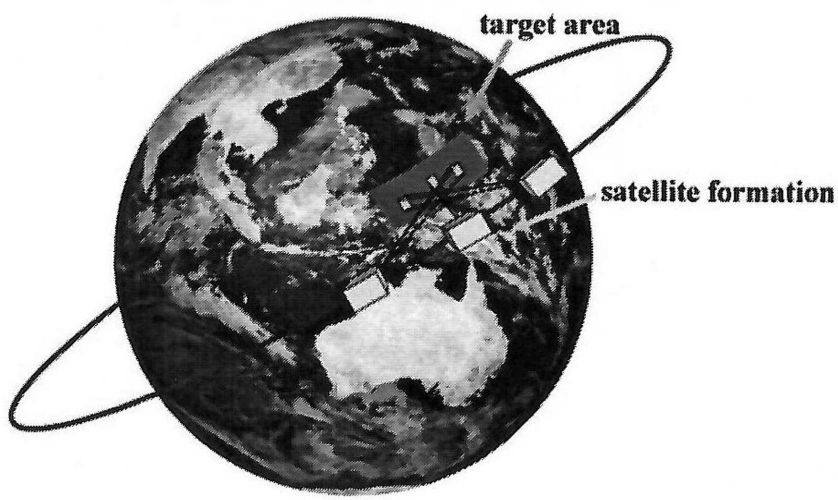
Although trough input, state and output spaces in terms of the classes of functions involved can be mathematically defined by chosen measuring norm, at any fixed time instant of time all vector-valued variables become real-valued vectors that simply may well be the Euclidean ones,. Thus also related directly to energy and power hence to stability **(A. M. Lyapunov. 1892) .**

0. PROLOG: PRESENTATION OUTLINE

- 1/. **Brief Introduction and Previous Works**
- 2/. **An Insight into Main Novel Results**
- 3/. **MATHEMATICAL BACKGROUND FOUNDATIONS**
- 4/. **A SAMPLE SET OF SIMULATION RESULTS**
- 5/. **CONCLUDING REMARKS**

Background Source Reference: S. Gao, Y. Jing, X. Liu, G. M. Dimirovski, "Chebyishev neural network-based attitude-tracking control for spacecraft with finite-time convergence." *International Journal of Control*, vol. 94, is.10, pp. 2712-2729, 2021.

1. Brief Introduction and Previous Works



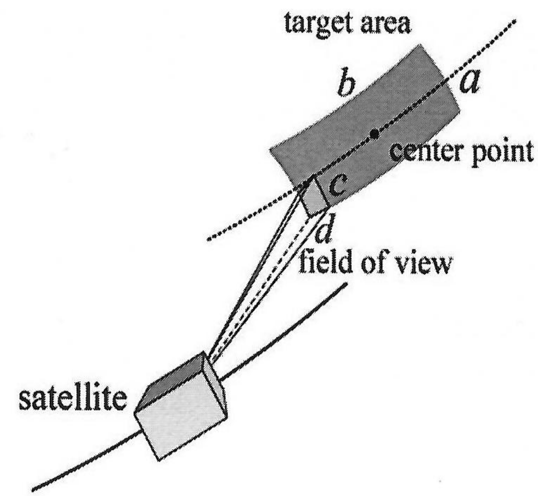


Figure 2. On Astronautic Engineering Problems: Operation imposing multiple mutually conflicting tasks in the target motion control as well as the controlled attitude and synchnronization at the achieved orbiting motion.

1. Brief Introduction and Previous Works

- The issues of system complexities, nonlinearities and uncertainties have been subject to study from the very beginnings of information theory as part of the theoretical studies in Engineering Cybernetics. Ultimately it has led to hierarchical organization of controlling infrastructure. Figure 3)
- However, there appear various kinds of complexities, nonlinearities and uncertainties in modeling dynamic objects and processes most often the parametric and structural uncertainties are being accounted for.
- Should we recognize the unavoidable need for some integrative organizational strategy imposed even in largely decentralized complex dynamic networks and systems, then complexities, nonlinearities and uncertainties too becomes as multi-faceted one as Natural Evolution processes appear. To be.
- At this point, it should be point to the largely neglected need for developing sophisticated theory on supervisory control strategies that can guarantee survivability of the complex dynamic networks and systems under various ad-hock topological circumstances via some controlled reinforcement of system integration .
- In my opinion, much too long time the issues of integrated regulatory servo-control and supervisory controls have been left over to more empirical investigations rather than theoretical studies. It is in this regard that I do believe computational cybernetics models and techniques are indispensible.

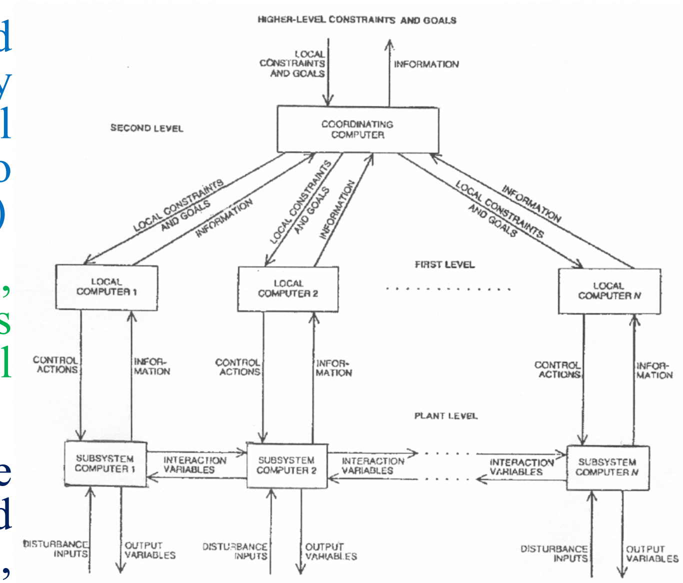


Figure 3. Hierarchical computer control based, implementation of integrated control and supervision [for complex dynamic networks and systems

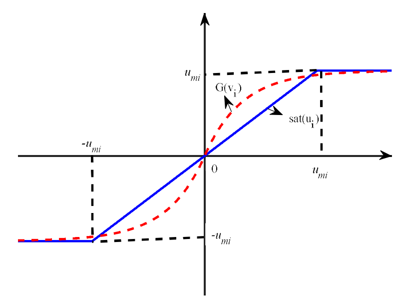


Figure 4. Acting Saturation nonlinearity in spacecraft controlled motion

1. Brief Introduction and Previous Works

- At this point in here, *now I would like to infer the issue of exploiting some hints from modern quantum theory, which seems to have been foreseen by Einstein his fellow-friends*.
- Namely, I think that *sooner or later we have the place our main focus on how to mitigate consequences of strict usage of the causality principle in systems and control science.*, or else at least to ameliorate it by limited employing of computation intelligence for emulating nonlinearity which involve uncertain variation of operating conditions.

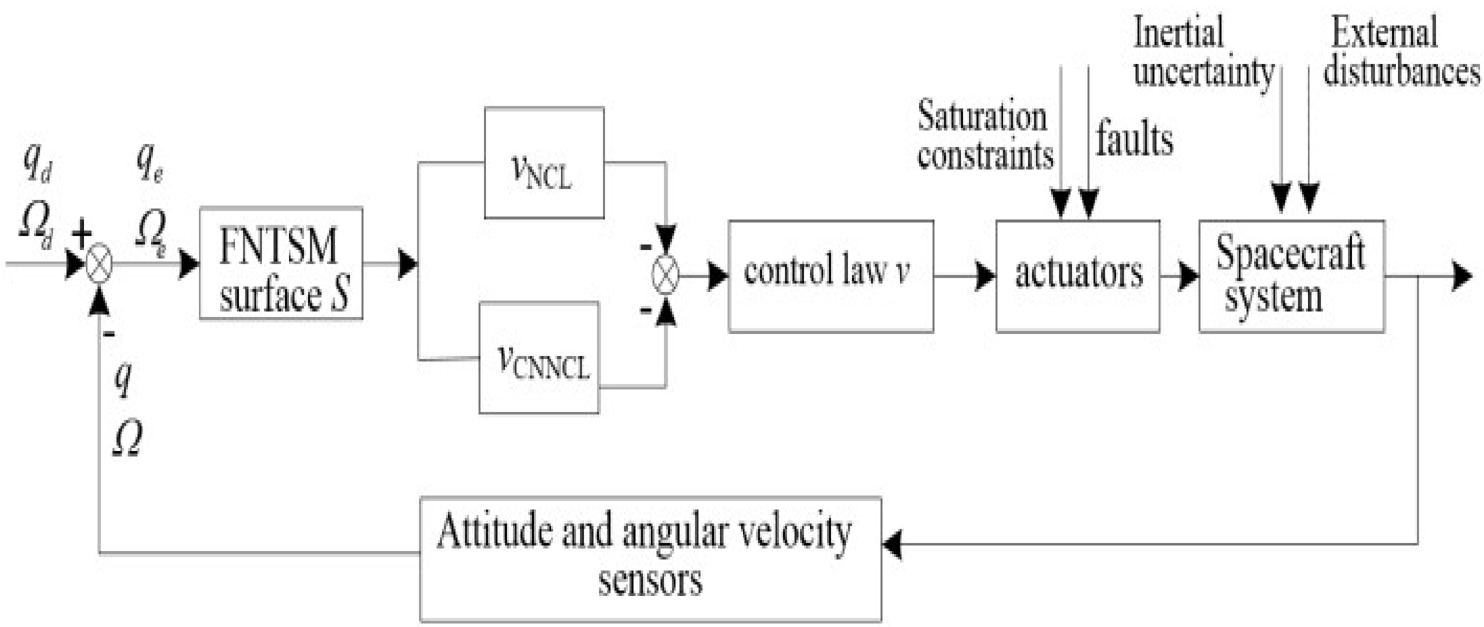


Figure 5 Innovated system architecture of the developed new spacecraft attitude integrated control and supervision system employing the FNTSM manifold and the CANN approximater.

3/. Mathematical Background Foundations

A. Kinematics and Dynamics of Rigid Spacecraft

The spacecraft in this paper is modeled as a rigid body with actuators providing torques along three mutually perpendicular axes which defines a body-fixed frame B. The equations of motion for a rigid spacecraft are conveniently (e.g. see [5], [6], [31] [32]) represented quaternions

$$\dot{q}_v = \frac{1}{2}(q_4 I_3 + q_v^{\times})\Omega, \quad \dot{q}_4 = -\frac{1}{2} q_v^T \Omega, \tag{1}$$

and thus it has been established:

$$J\dot{\Omega} = -\Omega^{\times} J \Omega + D\Gamma \mathrm{sat}(u) + d \, . \tag{2}$$

Here, the unit quaternion $q = [q_v^T, q_4]^T \in R^3 \times R$ represents the attitude orientation of the spacecraft in the body frame B with respect to the adopted inertial frame I, where $q_v = [q_1, q_2, q_3]^T \in R^3$ is the vector component and $q_4 \in R$ is the scalar component.

3/. Mathematical Background Foundations

As a non-singular attitude representation, the unit quaternion q satisfies the constraint $q_v^T q_v + q_4^2 = 1$, i.e., $\|q\| = 1$. $\Omega = [\Omega_1, \Omega_2, \Omega_3]^T \in R^3$ is the angular velocity of the body frame B relative to the inertial frame I, $J \in R^{3\times 3}$ is the symmetric inertial matrix; $u \in R^n$ ($n > 3$) is the torque vector produced by the n actuators and $d = [d_1, d_2, d_3]^T \in R^3$ is the vector of external disturbances. I_3 denotes the 3×3 identity matrix and $x^\times$ denotes the cross product operator on a vector $x = [x_1, x_2, x_3]^T$ given by

$$x^\times = \begin{bmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{bmatrix} \quad (3)$$

Property 1 [5], [42] The inertial matrix J is symmetric and positive definite, and satisfies the following bound condition: $J_1 \|x\|^2 \le x^T J x \le J_2 \|x\|^2$, where $\forall x \in R^3$, J_1 and J_2 are positive constants, respectively.

3/. Mathematical Background Foundations

Quantity $\Gamma = \text{diag}\{\Gamma_1, \ldots, \Gamma_n\} \in R^{n \times n}$ in (2) represents the actuator effectiveness matrix with Γ_i $(0 \le \Gamma_i \le 1)$, which also is the health indicator of the i-th actuator. The case $\Gamma_i = 1$ implies that the i-th actuator is healthy while the case $\Gamma_i = 0$ means that the i-th actuator loses its power totally. Note that when any actuator fails, the effectiveness matrix Γ becomes uncertain or time-varying but remains positive definite. Furthermore, quantity $D \in R^{3 \times n}$ in (2) represents the actuator distribution matrix. Notice that for a given spacecraft, D is available and it can be made full-row rank by properly placing the actuators at certain locations and directions of spacecraft body.

3/. MATHEMATICAL BACKGROUND FOUNDATIONS

Function $\text{sat}(u)=[\text{sat}(u_1),\text{sat}(u_2),\text{sat}(u_3)]^T$ defining the saturation constraint on the control input u, represents the actual control torque vector that actuators generate. The saturation function $\text{sat}(u_i)$ acting on the i-th actuator is

$$\text{sat}(u_i)=\begin{cases} u_i, & |u_i|\le u_{mi}, \\ u_{mi}\cdot \text{sgn}(u_i), & |u_i|>u_{mi}. \end{cases} \quad (4)$$

where u_{mi} is the limit of u_i , and $\text{sgn}(\cdot)$ denotes the '*sigmum*' function. A smooth function $G(v)=[G(v_1),G(v_2),G(v_3)]^T$ is introduced to approximate the saturation function

$$G(v_i)=\begin{cases} -u_M(1-e^{v_i}), & v_i<0, \\ 0 & v_i=0, \\ u_M(1-e^{-v_i}), & v_i>0. \end{cases} \quad (5)$$

where $u_M=\min(u_{mi})$, $i=1,2,3$. 0. The comparison result between the curves of $\text{sat}(u_i)$ and $G(v_i)$ is shown in Fig. 2. It is clear from Fig. 1 that the function $G(v_i)$ has the following property: $\text{sat}(G(v_i))=G(v_i)$. Furthermore, if we define $u_i=G(v_i)$, then $\text{sat}(u_i)=u_i$. Hence, it can be concluded that the function $G(\cdot)$ is qualified to simulate the input saturation constraint $\text{sat}(\cdot)$. Now, $v=[v_1,v_2,v_3]^T$ becomes the desired control law and will be designed to accomplish the tracking task (11)-(12).

3/. Mathematical Background Foundations

It should be noted from the background physics, the control law v_i and the sliding mode surface S_i to be designed are specified as follows:

$$\begin{cases} v_i < 0, & S_i > 0, \\ v_i = 0, & S_i = 0, \\ v_i > 0, & S_i < 0. \end{cases} \quad (6)$$

Assumption 1 [27] Consider the rigid spacecraft with n ($n > 3$) actuators that are properly mounted on it and thus $rank(D) = 3$. Even if all the actuators suffer from fading actuation or some of them fail completely, the remaining active actuators remain able to produce a sufficient control torque vector for the spacecraft system to perform the given maneuvers, as long as the completely failed actuators are no more than $n-3$ such that $D\Gamma D^T$ remains positive definite.

3/. Mathematical Background Foundations

B. On Spacecraft Attitude Tracking Error Model and Control Design Objective

In several of recent studies the attitude tracking error $q_e=[e_v^T, e_4]^T \in R^3 \times R$ with $e_v=[e_1, e_2, e_3]^T$ is defined as the relative orientation between the body frame B and the desired frame D with the desired orientation $q_d=[q_{dv}^T, q_{d4}]^T \in R^3 \times R$ where $q_{dv} := [q_{d1}, q_{d2}, q_{d3}]^T$. Unit quaternion q_e and q_d satisfy $\|q_e\|=1$ and $\|q_d\|=1$, respectively. According to the quaternion multiplication rule, the attitude tracking error q_e can be calculated as

$$e_v = q_{d4} q_v - q_{dv}^{\times} q_v - q_4 q_{dv}, \tag{7}$$

$$e_4 = q_{dv}^T q_v + q_4 q_{d4}, \tag{8}$$

The relative angular velocity $\Omega_e = \Omega - C\Omega_d$ with $\Omega_e = [\Omega_{e1}, \Omega_{e2}, \Omega_{e3}]^T \in R^3$ is defined in the body frame B with respect to the desired frame D, where $\Omega_d = [\Omega_{d1}, \Omega_{d2}, \Omega_{d3}]^T \in R^3$ is the desired angular velocity. The rotation matrix is $C = (e_4^2 - e_v^T e_v) I_3 + 2 e_v e_v^T - 2 e_4 e_v^{\times}$ with $\|C\|=1$ and $\dot{C} = -\Omega_e^{\times} C$.

3/. Mathematical Background Foundations

Notice that q_v and $-q_v$ represent the same physical attitude orientation and results in the same C. The desired attitude motion is generated by means of $\dot{q}_{dv} = \frac{1}{2}(q_{d4} I_3 + q_{dv}^{\times})\Omega_d$, $\dot{q}_{d4} = -\frac{1}{2} q_{dv}^{T} \Omega_d$. Thus, the attitude tracking error model can be stated as follows:

$$\dot{e}_v = \frac{1}{2}(e_4 I_3 + e_v^{\times})\Omega_e, \quad \dot{e}_4 = -\frac{1}{2} e_v^{T} \Omega_e \tag{9}$$

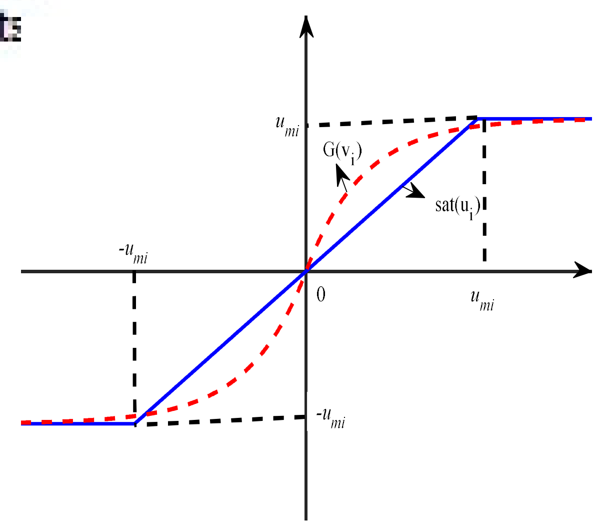
$$J\dot{\Omega} = -(\Omega + C\Omega_d)^{\times} J(\Omega + C\Omega_d) + J(\Omega^{\times} C\Omega_d - C\dot{\Omega}_d) + D\Gamma G(v) + d \tag{10}$$

***Assumption** 2* [27] The desired angular velocity Ω_d and its first derivative $\dot{\Omega}_d$ are bounded at all times.

Chebyshev polynomials can be obtained using the two-term recursive formula [23], which is defined by equation

$$T_{i+1}(x) = 2x T_i(x) - T_{i-1}(x) \quad , T_0(x) = 1 \tag{13}$$

where $x \in R$ and $T_1(x)$ can be defined as x, $2x$, $2x-1$, $2x+1$, etc.



3/. MATHEMATICAL BACKGROUND FOUNDATIONS

The primary aim of this investigation is a control system design such that the spacecraft state variables in the closed-loop system described by (9) and (10) converge into small regions surrounding the origin in finite time even when actuator failures, external disturbances, inertial uncertainties, and saturation constraints arise occasionally or concurrently. Thus, the control objective is formulated as simultaneous

$$\lim_{t \to T_f} e_i(t) \to \Delta_e, \tag{11}$$

$$\lim_{t \to T_f} \Omega_{ei}(t) \to \Delta_\Omega, \tag{12}$$

where T_f is the settling time, Δ_e and Δ_Ω are the convergence domains of attitude tracking error $e_i(t)$ and angular velocity tracking error $\Omega_{ei}(t)$, respectively, for $i = 1, 2, 3$. The overall structure of the envisaged control scheme is shown in Fig. 4. In there, term v_{NCL} is the nominal control law (NCL) while term v_{CNNCL} is the CANN based control law (CNNCL) that serves the compensation for the nonlinear uncertain term.

3/. Mathematical Background Foundations

Actuator Nonlinearity Approximation by Chebyshev ANN Emulator

Hence, the unknown nonlinear function $N(\Omega,q)$ that naturally appears in the differential equation of the sliding surface [27] as follows

$$N_d(\Omega_d,\dot{\Omega}_d) = -\Omega_d^{\times} J\Omega_d - J\dot{\Omega}_d + d\ , \qquad (17)$$

which in the next subsection will be shown to converge to the desired unknown function $N_d(\Omega_d,\dot{\Omega}_d) \in R^3$. Let define the augmented state $U = [\Omega_d^T, \dot{\Omega}_d^T]^T$. Based on Assumption 4, the following compact set can be obtained:

$$U_\Omega = \{U \mid \|U\| \le U_M,\ U_M > 0\} \qquad (18)$$

Using the aforementioned approximation property of CNN, the unknown function $N_d(\Omega_d,\dot{\Omega}_d)$ can be approximated as

$$N_d(\Omega_d,\dot{\Omega}_d) = \zeta^T(\Omega_d,\dot{\Omega}_d)\boldsymbol{W}^* + \boldsymbol{\delta} \qquad (19)$$

where $\zeta(\Omega,q) = \mathrm{blkdiag}\{\xi_1(\Omega,q), \xi_2(\Omega,q), \xi_3(\Omega,q)\}$ with blkdiag{} denoting a quasi-diagonal matrix, $\boldsymbol{W}^* = [(W_1^*)^T, (W_2^*)^T, (W_3^*)^T]^T$ and $\boldsymbol{\delta} = [\delta_1, \delta_2, \delta_3]^T$. Then the differential equation of the sliding surface (17) can be written as

$$J\dot{S} = D\Gamma G(v) + \chi + \zeta^T(\Omega_d,\dot{\Omega}_d)\boldsymbol{W}^* + \boldsymbol{\delta} \qquad (20)$$

where $\chi = N(\Omega,q) - N_d(\Omega_d,\dot{\Omega}_d)$ denotes error between $N(\Omega,q)$ and the desired nonlinear function $N_d(\Omega_d,\dot{\Omega}_d)$.

3/. Mathematical Background Foundations

Guidance to Construction of Fast Nonsingular Terminal Sliding-mode Manifold

The Fast-NTSM technique is adopted by authors of [40], and was further employed in [27], [31] as well as here. A Fast-NTSM surface composed of attitude tracking error and angular velocity tracking error is constructed as

$$S = \Omega_e + K_1 e_v + K_2 S_{aux} \; . \qquad (21)$$

Quantities denote: $S = [S_1, S_2, S_3]^T \in R^3$, $K_j = \mathrm{diag}\{K_{ji}\}$, $K_{ji} > 0$, $j = 1, 2$, $i = 1, 2, 3$, and $S_{aux} = [S_{aux1}, S_{aux2}, S_{aux3}]^T$ designed as follows:

$$S_{auxi} = \begin{cases} e_i^r, & \text{if } (\bar{S}_i = 0) \text{ or } (\bar{S}_i \neq 0, |e_i| \geq \varepsilon), \\ l_1 e_i + l_2 \mathrm{sgn}(e_i) e_i^2, & \text{if } (\bar{S}_i \neq 0, |e_i| < \varepsilon). \end{cases} \qquad (22)$$

In here, $\bar{S}_i = \Omega_{ei} + K_{1i} e_i + K_{2i} e_i^r$, $0 < r = r_1 / r_2 < 1$, r_1, r_2 are positive odd integers. According to [45], $l_1 = (2 - r)\varepsilon^{r-1}$, $l_2 = (r-1)\varepsilon^{r-2}$, $\varepsilon > 0$ is a small positive constant. With regard to the spacecraft system described by (9)-(10) and the Fast-NTSM manifold surface (17), the differential equation of the sliding surface obtained [27] is

$$J\dot{S} = D\Gamma G(v) + N(\Omega, q) \qquad (23)$$

where

$$N(\Omega, q) = -(\Omega_e + C\Omega_d)^{\times} J(\Omega_e + C\Omega_d) + J(\Omega_e^{\times} C\Omega_d - C\dot{\Omega}_d) + \frac{1}{2} J(K_1 + K_2 E)(e_4 I_3 + e_v^{\times})\Omega_e + d \qquad (24)$$

and E is defined as

$$E := \begin{cases} r\,\mathrm{diag}(e_i^{r-1}), & \text{if } (\bar{S}_i = 0) \text{ or } (\bar{S}_i \neq 0, |e_i| \geq \varepsilon), \\ l_1 I_3 + 2 l_2 \mathrm{diag}(\mathrm{sgn}(e_i) \cdot e_i), & \text{if } (\bar{S}_i \neq 0, |e_i| < \varepsilon). \end{cases} \qquad (25)$$

3/. Mathematical Background Foundations

Main New Results

Theorem 1 Consider the spacecraft system governed by (1) and (2), and suppose Assumptions 1-4 and Properties 1-2 are satisfied. All signals in the closed-loop system are UUB under the compound control law (27)

$$v(t) = -\tau D^T S - v_{CNNCL} \quad (27)$$

The CANN control law v_{CNNCL} and the adaptive law $\dot{\hat{W}}_s$ are designed, respectively, by means of Eqs. (28) and (29)

$$v_{CNNCL} = \begin{cases} \frac{1}{2\mu^2} \hat{W}_s^T \Xi D^T S, & \text{if } \|S\| \hat{W}_s^T \Xi > \epsilon, \\ \frac{D^T S}{\epsilon} \left(\frac{1}{2\mu^2} \hat{W}_s^T \Xi\right)^2 & \text{otherwise,} \end{cases} \quad (28)$$

$$\dot{\hat{W}}_s = \beta_1 \left(\frac{\|S\|^2}{2\mu^2} \Xi - \beta_2 \hat{W}_s\right), \quad (29)$$

where $\Xi = (\|\zeta(\Omega, q)\|^2, 1)^T$ is the extended basis function, $W_s = (\|W^*\|^2, \|\delta\|^2)^T$ is the extended optimal weight matrix, $\hat{W}_s$ is the estimation of W_s, $\epsilon > 0$ is a small constant scalar, and $\tau > 0$, $\mu > 0$, $\beta_1 > 0$ and $\beta_2 > 0$ are adjustable parameters for fine tuning. The proof is found in [27].

3/. Mathematical Background Foundations

Main New Results

Theorem 2 Consider the spacecraft system governed by (1) and (2), and suppose Assumptions 1-4 and Properties 1-2 are satisfied. Then Fast-NTSM manifold S_i converges to region Δ_S in finite time T_{reach} in closed loop under the control law (38) and adaptive law (29) hnce the attitude tracking error $e_i(t)$ and also angular-velocity tracking error $\Omega_{ei}(t)$, respectively, converge into regions Δ_e and Δ_Ω in finite time T_f that are shown below

$$\Delta_S = \max\left\{\min\left\{\Delta_{S_{A1}}, \Delta_{S_{A2}}\right\}, \min\left\{\Delta_{S_{B1}}, \Delta_{S_{B2}}\right\}\right\} \quad (30)$$

$$\Delta_e = \max\left\{\varepsilon, \frac{\Delta_S}{2K_{1\min}}, \sqrt{\frac{\Delta_S}{2K_{2\min}}}\right\} \quad (31)$$

$$\Delta_\Omega = \Delta_S + K_{1\max}\Delta_e + K_{2\max}(\Delta_e)^r \quad (32)$$

where:

$$\Delta_{S_{A1}} = \sqrt{\frac{J_2\Phi_3}{J_1(\tau\rho - \frac{1}{2\mu^2})}} \text{ with } \tau\rho > \frac{1}{2\mu^2}, \quad (33)$$

$$\Delta_{S_{A2}} = \sqrt{\frac{J_2}{J_1}\left(\frac{\Phi_3}{\rho\sigma_{\min}}\right)^{2/(\alpha+1)}}, \quad (34)$$

$$\Delta_{S_{B1}} = \sqrt{\frac{J_2\Phi_4}{J_1(\tau\rho - \frac{\rho\epsilon}{4} - \frac{1}{2\mu^2})}} \text{ with } \tau\rho > \frac{\rho\epsilon}{4} + \frac{1}{2\mu^2}, \quad (35)$$

$$\Delta_{S_{B2}} = \sqrt{\frac{J_2}{J_1}\left(\frac{\Phi_4}{\rho\sigma_{\min}}\right)^{2/(\alpha+1)}} \text{ with} \quad (36)$$

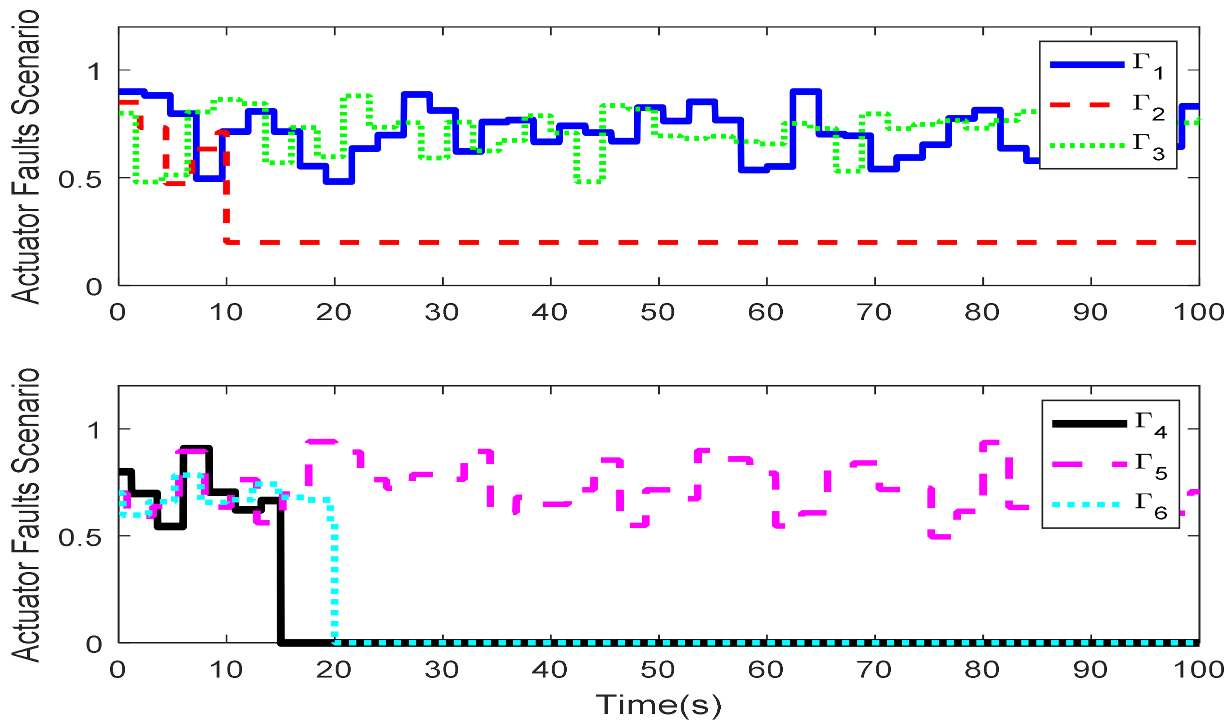
$$\Phi_3 = \frac{1}{2}\mu^2\chi_M^2 + \mu^2 + \chi_{Au}\,\&\,\Phi_4 = \frac{\chi_{Au}\sqrt{\beta_i\chi_U}}{2\epsilon\mu^2\sqrt{\rho}} + \frac{1}{2}\mu^2\chi_M^2 + \mu^2, \quad (37)$$

and $\sigma_{\min} = \min\{\sigma_1, \sigma_2, \sigma_3\}$, $i = 1,2,3$ along with compound control law

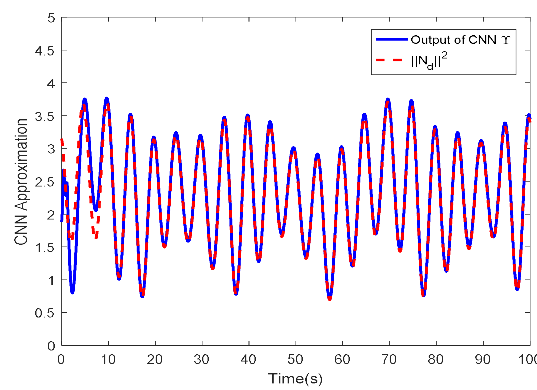
$$v_1(t) = -\tau D^T S - D^T\sigma S^\alpha - v_{CNNCL}, \quad (38)$$

in which $S^\alpha = [S_1^\alpha, S_2^\alpha, S_3^\alpha]^T$, $\sigma = \mathrm{diag}\{\sigma_1, \sigma_2, \sigma_3\}$ with $\sigma_i > 0$, $i = 1,2,3$, and $0 < \alpha = p_1/p_2 < 1$ with p_1, p_2 being positive odd integers. The CANN based control law v_{CNNCL} and adaptive law $\dot{\hat{W}}_z$ have the same role as in Eqs. (27) and (29), respectively. The proof is found in [27].

4/. A Sample Set Of Simulation Results

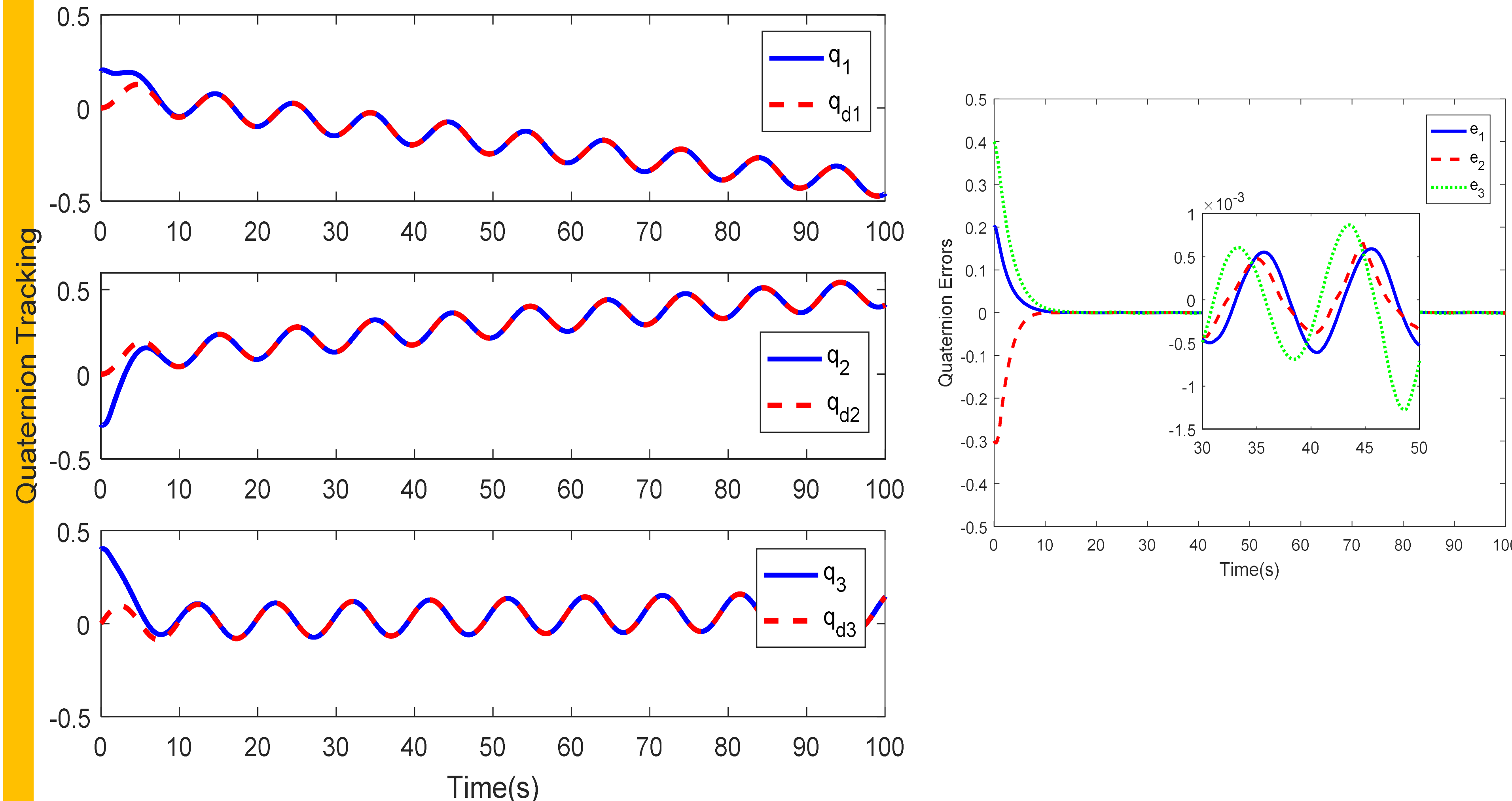


- Fig. Exp3 Actuators Fault Scenario in Simulation Experiments



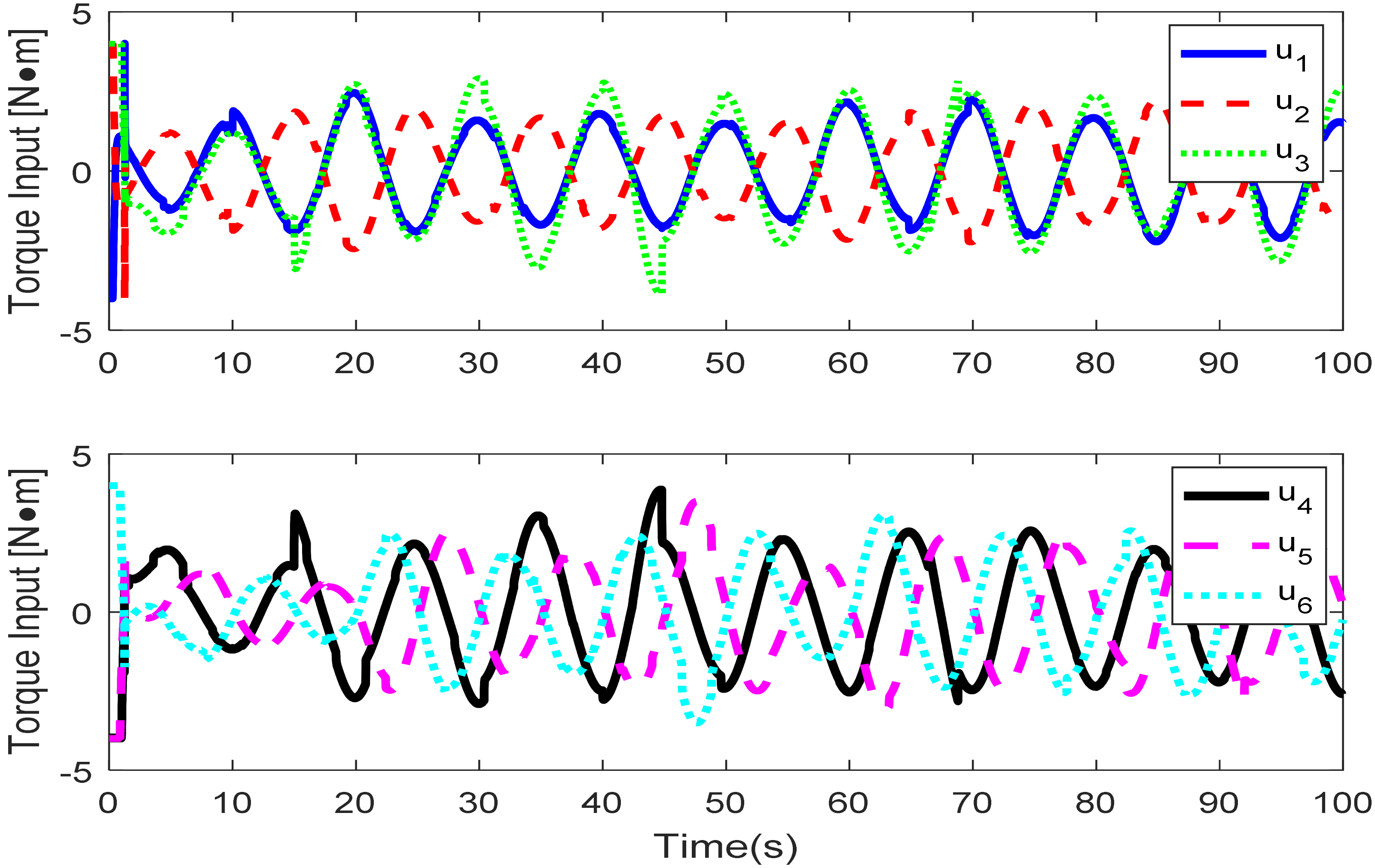
- Fig. Exp4 Approximation performance of CANN emulator

4/. A Sample Set Of Simulation Results



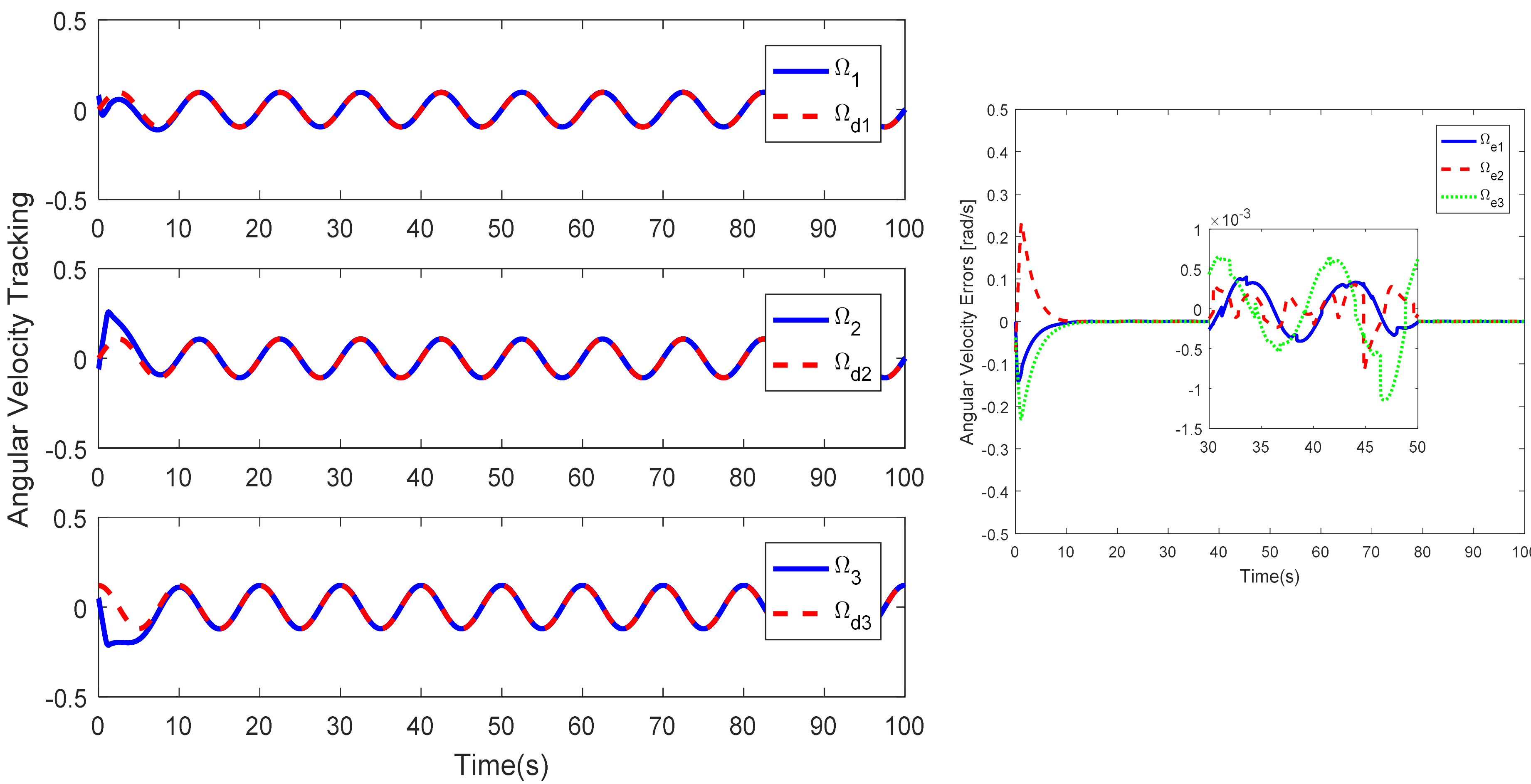
- Fig, Exp4-5 Quaternion tracking responses and its performance

4/. A Sample Set Of Simulation Results



- Fig. Exp6 Control inputs corresponding to fault scenario: controlling torques responses

4/. A Sample Set Of Simulation Results



Fig, Exp7 Angular tracking according to fault scenario and its performance

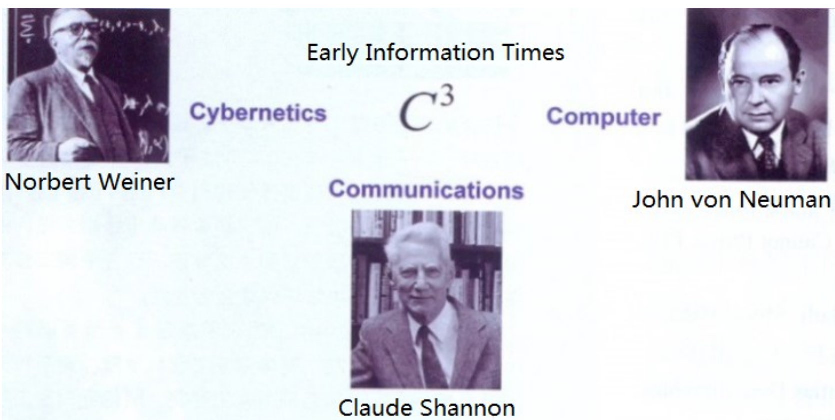
5/. Concluding Remarks

The finite-time attitude tracking control problem for a rigid spacecraft is investigated and solved with the aim to design a robust fault-tolerant controller that guarantees uniformly bounded quality tracking performance in the finite time. The essential issues – inertial uncertainties, external disturbances, actuator failures, and input saturation – are accounted for in this fault-tolerant control system design. **Combined usage of the CANN approximation and the Fast-NTSM adaptive control synthesis along with angular velocity measurements ensures all system signals in the closed-loop operation remain ultimately uniformly bounded at all times.**

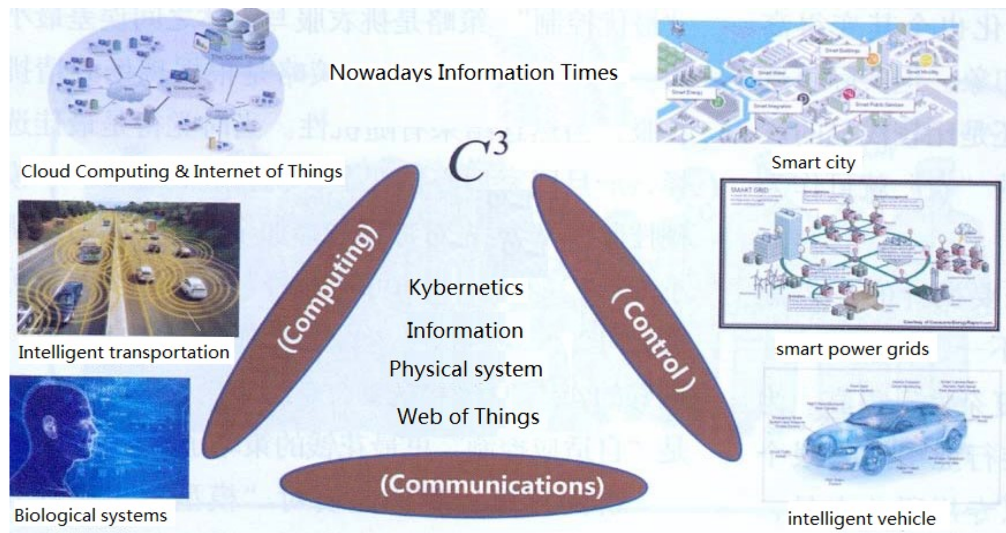
The future research is envisaged into a further exploration of these findings in order to transcend them into novel ideas on how to combine techniques of ANN emulator and Fast-NTSM manifold with the same control system architecture for flexible and variable-structure spacecrafts [39]-[41]. An entirely new prospect for tackling spacecraft attitude control is believed lies hidden within the synergies of combining switching control of nonlinear systems with sliding-mode manifold surface synthesis [42]-[44] along with fuzzy-rule [45] or neural-network [46] switched systems.

INSTEAD OF END TO CONCLUDING REMARKS

I incline to believe, we should follow path of late Academician Hsue-Sen Tzien's Vision of Engineering Cybernetics right precisely as He has foreseen the C3 synergies half a century ago..



The Founders of early C3 paradigm in nowadays man-modified world

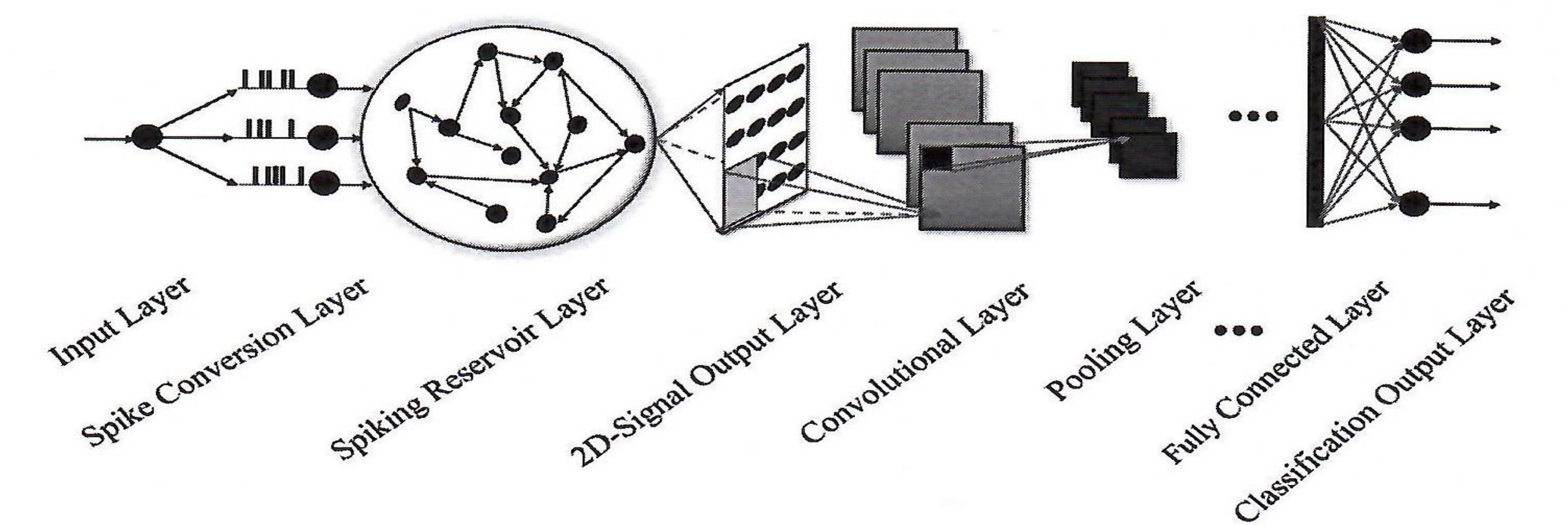


Nowadays man-modified world that is already Shaping tomorrow 's man-modified world

Thank you so much my Honorable Colleagues for listening to me!

Instead of End to Concluding Remarks

Let full freedom to your intuition and imagination in order to establish mutual relationships between the previous talking of mine and the next indicative hint (IEEE Access, 2019, 7: 4927-4935) illustration designed by A. Zhang. W. Zhu and J. Li, Hefei Technology College, Hefei, China.



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