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DEVELOPMENT OF A FORMAL MODEL OF AN ADAPTIVE ERGATIC SHIP MOTION CONTROL SYSTEM

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Introduction. The modern maritime transport sector faces a number of challenges: traffic intensity in coastal and port areas, weather conditions, and multisensor navigation aids, among others. Under such conditions, a navigator must simultaneously process data from radar, AIS, ECDIS, engine-and-hydraulic system sensors, and electrical system sensors. Autopilot automation and warning systems are focused on the technical and navigational aspects of ship dynamics, but they do not treat the human operator—the navigator—as the central element of the ergatic motion-control system. Although ECDIS alarms, phantom trajectory visualizations, and AIS target overlays are continuously active in real time, the navigator does not always perceive the situation objectively [1].

Therefore, there is a need to develop an integrated formal model that implements situational control of the ergatic ship-motion system, in which automation modes, support algorithms [2], and bridge-deck interfaces dynamically adapt to the current risk level in the waterway, the watch-team's workload, and the navigator's psychophysiological state.

Main body of the study.

Taking into account the relevance of the study, we now turn to the construction of a formal model of the adaptive ergatic ship-motion control system.

1. Definition of model parameters and state vector.

We introduce the following components: ship physical parameters: course, speed, position, autopilot engagement level; operator psychophysiological state; external navigational factors: closest-point-of-approach distance (CPA), traffic density, wave height, visibility, wind speed, current speed; navigation-situation perception index.

1.1. Continuous state (1).

$$x(t)=\begin{bmatrix}\varphi(t)\\ V(t)\\ p(t)\\ z(t)\end{bmatrix},\ h(t)\in[0,1], \tag{1}$$

where,

$\varphi(t)$ — is the ship's course (degrees),

$V(t)$ — is the ship's speed (knots),

$p(t)$ — is the ship's position (Lat, Lon),

$z(t)$ — is the autopilot activation level,

$h(t)$ — is the navigator's cognitive workload (dimensionless).

1.2. External-navigation-factor vector (2).

$$c(t)=\left[d_{CPA},p_{AIS},H_{wave},V_{vis},W_{wind},C_{current}\right], \tag{2}$$

where,

d_{CPA} — is the distance to the closest point of approach,

p_{AIS} — is the vessel density,

H_{wave} — is the wave height,

V_{vis} — is the visibility range,

W_{wind} — is the wind speed,

C_{current} — is the current speed.

1.3. Perception adequacy coefficient [3] (3).

$$q\left(t\right)=R_{nav}e^{-\alpha_h h(t)}\cdot e^{-\alpha_T T_{scan}(t)}\cdot e^{-\alpha_S \frac{S(t)}{N_{\max}}}, \tag{3}$$

where,

$q\in[0,1]$ — is the navigator's perception quality,
R_{nav} — is the reliability of the navigation equipment,
T_{scan} — is the situation-scan periodicity,
$S(t)$ — is the number of active information channels on the bridge,
$N_{\max}$ — is the maximum number of channels the operator can process,
α_{h}, α_{T}, $\alpha_{\text{S}} > 0$ – are sensitivity coefficients.

1.4. Risk index [4] (4).

$$R\left(t\right)=\sum_{i=1}^{4}w_i\tilde{c}_i\left(t\right),\ \tilde{c}_1=1-\frac{d_{CPA}}{D_{\max}},\tilde{c}_2=\frac{p_{AIS}}{p_{\max}},\tilde{c}_3=\frac{H_{wave}}{H_{\max}},\tilde{c}_4=\frac{1}{V_{vis}/V_{\max}}, \tag{4}$$

where,

w_i — factor weights ($\sum w_i=1$),
$D_{\max}$, $p_{\max}$, $H_{\max}$, $V_{\max}$ — are normalization constants.

2. Discrete risk-level modes (5).

$$\sigma\left(t\right)\in\left\{LowRisk, MedRisk, HighRisk\right\},\sigma=\begin{cases}LowRisk,\ R<\rho_1,\\ MedRisk,\ \rho_1\le R<\rho_2,\\ HighRisk,\ R\ge\rho_2.\end{cases}\qquad \rho_1,\rho_2\in\left(0,1\right). \tag{5}$$

3. Continuous dynamics in each mode [5, 6] (6).

$$\begin{aligned}&\dot{\varphi}=\omega_{AP}\left(\sigma\right)\mu u_{AP}+k_{rudder}\left(\sigma\right)\left(1-\mu\right)u_{rudder}+k_{wind}W_{wind}\cos\left(\psi_{wind}-\varphi\right),\\&\dot{V}=a_{eng}\left(\sigma\right)u_{eng}-r_{drag}\left(V\right)+k_{curr}C_{curr}\cos\left(\theta_{curr}-\varphi\right),\\&\dot{p}=V\left[\cos\varphi,\sin\varphi\right]^T,\\&\dot{z}=\Phi_\sigma\left(x,z\right),\\&\dot{h}=-\alpha\left(\sigma\right)h+\sum_{i=1}^{6}\beta_i\left(\sigma\right)\tilde{c}_i\left(t\right),\end{aligned} \tag{6}$$

where,

u_{AP} — is the autopilot control,
u_{rudder} — is the rudder control,
u_{eng} — is the engine-mode control,
$\mu\in\left[0,1\right]$ — is the automation level.
$\omega_{AP}, k_{rudder}, a_{eng}, \alpha, \beta_i$ — are mode function σ.

4. Discrete transitions taking into account operator's situation perception (7).

$$\sigma^+=\gamma\left(R,h,q\right)=\begin{cases}LowRisk,\ R<\rho_1\wedge h<h_{th1}\wedge q>q_{th1},\\ MedRisk,\ \left(\rho_1\le R<\rho_2\right)\vee\left(h_{th1}\le h<h_{th2}\right)\vee\left(q_{th2}<q<q_{th1}\right),\\ HighRisk,\ R\ge\rho_2\vee h\ge h_{th2}\vee q\le q_{th2},\end{cases} \tag{7}$$

where,

$h_{\text{th1}}< h_{\text{th2}}$, $q_{\text{th1}}> q_{\text{th2}}$ are — thresholds.

5. Adaptive automation (8).

$$\mu^{+}=\mathrm{A}\left(R,h,\sigma,q\right),\begin{cases}\mu\rightarrow 1,\ \sigma=LowRisk\wedge h<h_{low}\wedge q>q_{high},\\ \mu\sim 0{,}5,\ \sigma=MedRisk\wedge\left(q_{low}<q\leq q_{high}\right),\\ \mu\rightarrow 0,\ \sigma=HighRisk\vee q\leq q_{low}\vee h>h_{high}.\end{cases}\tag{8}$$

6. Complete hybrid ergatic-system model (9).

$$\begin{aligned}&\dot{x}=f_{\sigma(t)}\left(x,u,\mu(t)\right),\\&\dot{h}=\delta_{\sigma(t)}\left(h,c(t)\right),\\&q(t)=\Psi\left(h(t),T_{scan}(t),R_{nav},S(t)\right)\\&\sigma^{+}=\gamma\left(R(t),h(t),q(t)\right),\\&\mu^{+}=\mathrm{A}\left(R(t),h(t),\sigma(t),\ q(t)\right).\end{aligned}\tag{9}$$

7. Analysis of unified scenarios (Table 1).

Table 1. Unified data for risk modeling

Scenarios	R	h	q	μ	σ
Open sea	0,15	0,2	0,85	0,90	LowRisk
Harbor	0,45	0,6	0,55	0,50	MedRisk
Port	0,75	0,8	0,25	0,10	HighRisk

8. Determination of perception-adequacy thresholds.

8.1. Information-load model for the navigator-operator (10).

$$\lambda_S(t)=\frac{S(t)}{N_{\max}}.\tag{10}$$

$S(t)$ — is the number of active sources.

$N_{\max}$ — is the operator's maximum information-processing capacity.

8.2. Modified formula incorporating perception quality λ (11).

$$q(t)=R_{nav}e^{-\alpha_h h}e^{-\alpha_T T_{scan}}e^{-\alpha_S\lambda_S}.\tag{11}$$

8.3. Threshold determination.

Experimental calibration: series of tests with varying S, T_{scan}, and h; collection of performance P(time, errors)

Construction of the performance function (12):

$$P(q)\approx\frac{1}{1+\exp\left(-a\left(q-q_0\right)\right)}.\tag{12}$$

Threshold selection.

q_{95} — is the navigator succeeds at least 95 % of the time under demanding but controlled conditions,

q_{80} — is the baseline acceptability of operator actions (80 % success) (13).

$$q_{95}=q_0+\frac{1}{a}\ln\frac{0{,}95}{0{,}05},\ q_{80}=q_0+\frac{1}{a}\ln\frac{0{,}80}{0{,}20}\Rightarrow q_{th1}=q_{95},\ q_{th2}=q_{80}.\tag{13}$$

Thus, a functional accounting for individual perception thresholds of navigational situations by operators is obtained.

Conclusion. The proposed formal model will ensure: state completeness: tracking of ship physical parameters (φ, V, p, z), operator cognitive load (h), external navigational factors (CPA, traffic, waves, visibility, wind, current), plus perception (q) and risk (R) indices as two scalars to support decision making.

Situational risk classification: based on R, the system switches to one of three modes (LowRisk, MedRisk, HighRisk) corresponding to open sea, harbor, or port, enabling adaptive support strategies and automation.

Hybrid dynamics: in each mode, differential equations describe ship motion (rudder, engine modes, external forces) and change in h; their parameters depend on mode σ and automation μ, providing integrated human–machine–environment modeling.

Adaptive transitions: the function $\gamma(R, h, q)$ instantly changes mode σ when thresholds ($\rho_{1,2}$, $h_{th1,2}$, $q_{th1,2}$) are crossed, and the rule $A(R, h, \sigma, q)$ adjusts automation level μ, ensuring rapid reaction to threats and workload.

Personalized q_{th} thresholds: perception coefficient q accounts for cognitive state, scan frequency, and multitasking; thresholds q_{95} and q_{80} are computed via a logistic curve $P(q)$ with individual operator parameters, adapting to their processing capacity.

Practical significance: combining ship-motion modeling with automatic identification of psychophysiological and situational states creates a single ergatic system capable of real-time adjustment of control and support modes [7-9].

The approach paves the way for future simulation-based extensions to handle more complex navigational scenarios and operator states.

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