МИНИСТЕРСТВО НАУКИ
И ВЫСШЕГО ОБРАЗОВАНИЯ
РОССИЙСКОЙ ФЕДЕРАЦИИ

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Model-based and algorithmic support for proactive control of distributed measurements and calculations performed by a multi-satellite constellation

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Abstract

- We present hybrid analytical-simulation, logical-dynamic and neuro-symbolic models, methods and algorithms for proactive planning and scheduling of distributed measurement and computing operations (MCO) of a multi-satellite constellation (MSC) of heterogeneous small Earth remote sensing satellites.
- The onboard hardware and software of each satellite are assumed to acquire, store, process and transmit information to other satellites and to its consumers.
- Our earlier approach to synthesising technologies and programs for controlling information processes in the Industrial Internet of Things is transformed to organise distributed space measurements and computations.
- The results rest on dynamic decomposition of the integrated MCO planning problem and on dynamic constraints: only the currently relevant operations are considered at each step.
- Neuro-symbolic models provide multi-variant and prompt forecasts of plan execution; plans and schedules are generated by logical-dynamic analytical-simulation models and algorithms.

Outline

1 Introduction

2 State of the Art

3 Materials and Methods

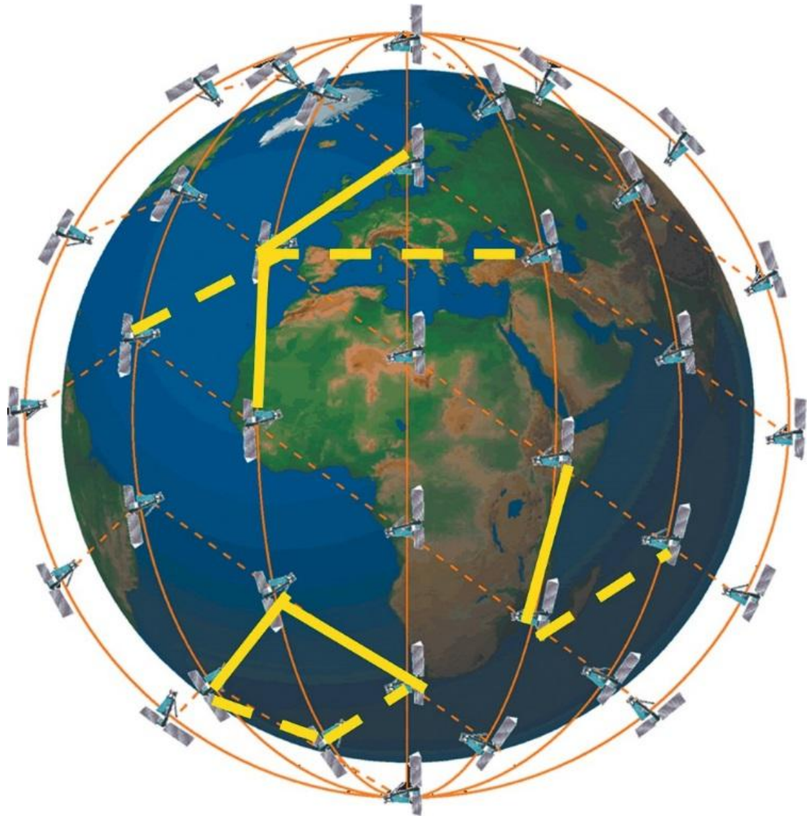
4 Results

5 Discussion and Conclusion

1. Introduction

Introduction: space computing

- Research on space computing has moved from theoretical results to the first on-orbit implementations [1].
- A three-tier edge-fog-cloud architecture is the most promising for MSCs of heterogeneous satellites with high-performance onboard computers and inter-satellite links, including laser links.
- This makes it possible to build network structures in space, e.g. clusters of large, medium and small satellites [2].
- The space-based Industrial Internet of Things (Space-based IIoT), built on artificial intelligence, combines IIoT with proactive MSC control and space computing (SC).



Inter-satellite information exchange in an MSC

Introduction: space computing and the research problem

Space computing: processing, storage, transmission of data and AI computations move to the orbits of the MSC

- reduces the load on ground data centres
- enables ultra-fast analysis of satellite data
- relieves congestion of the global internet
- provides natural cooling of distributed computing capacity

A pressing problem is to develop the scientific foundations of one of the central subsystems of the space-based IIoT: special model-based and algorithmic support for proactive control of measurement and computing operations (MCO) in an MSC under a changing external disturbing environment.

Sources of data and information for MCO: service objects (SO)

ground	**airborne**	**water**	**space, including the MSC satellites themselves**

2. State of the Art

State of the Art: common limitations

> **Almost none of the reviewed works treats holistically the general statement and solution of structural-functional synthesis of technologies and programs for proactive control of information and computing processes in dynamic MSC structures.**

Common limitations [9]:

- orbital structural dynamics is not considered in proactive (anticipatory) MCO planning and control;
- insufficient attention to disturbing factors: space environment factors, information security;
- insufficient attention to energy consumption when executing control programs;
- no standardisation of interaction between constellations in different orbits.

The paper uses proactive MCO control in an MSC to illustrate the main ideas of organising space computing on the basis of space-based IIoT

3. Materials and Methods

3.1. Methodology: the main resource allocation problem

Industrial internet methodology [11, 12]: information-control and infocommunication processes based on integrated cloud, edge and fog computing.

Proactive control programs for MCO and ICO

can be determined only after the structures of technologies, functions and algorithms of information processing and control in the space-based IIoT are known

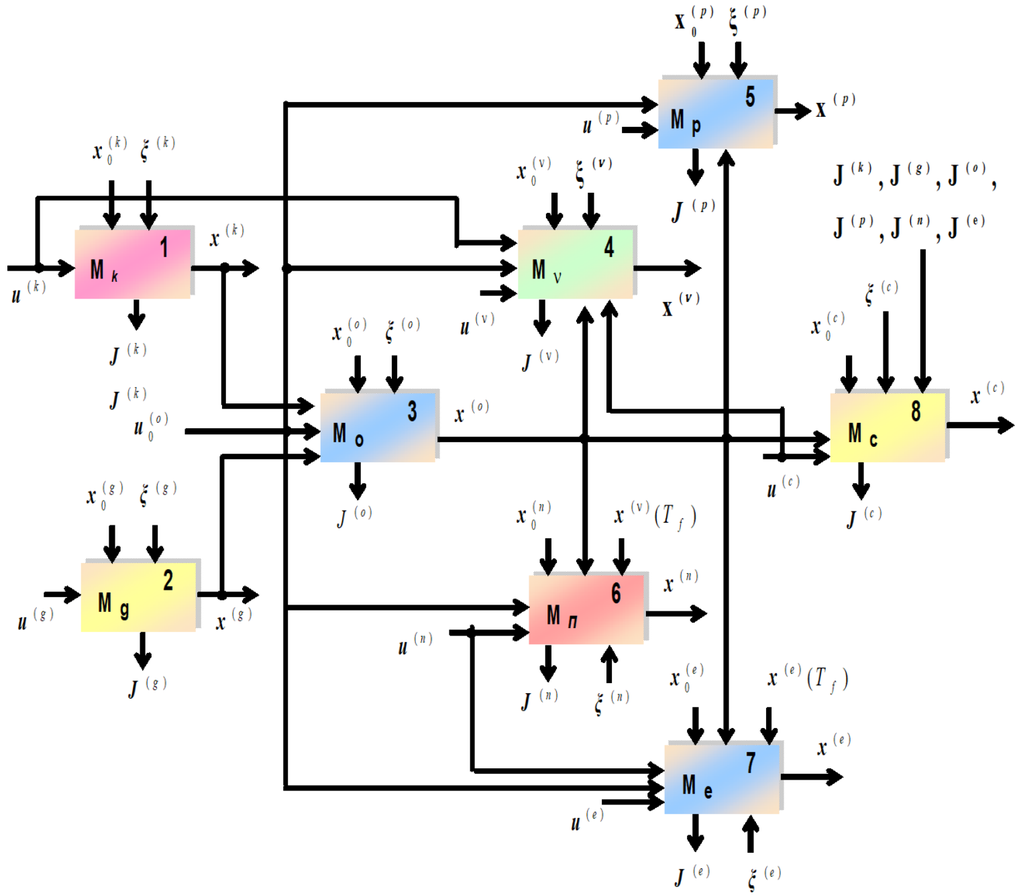
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Allocation of functions and algorithms

to MCO and ICO elements and subsystems depends on the structure and parameters of the plans and laws controlling these elements and subsystems

Determining control programs and allocating functions are interdependent [1-5, 10-12].

Level 1: logical-dynamic models of proactive planning



Analytical-simulation logical-dynamic models of proactive planning [13-15]

- M_o: dynamic model of program control of MCO, formula (5)
- M_e: dynamic model of proactive planning of measurement accuracy, formula (6)
- the models are linked through constraints on the controls $u^{(e)}$ and $u^{(o)}$

3.2. Poly-model description: problem statement

Proactive planning of observation satellite operation for MCO (a subset of interaction operations, IO):

- find an admissible proactive control program for MCO and satellites (a proactive, anticipatory operating plan),
- whose execution completes all operations of the technological control cycles (TCC) of the MSC fully and on time,
- while the quality of estimating the state of service objects meets the specified requirements.

> **If there are several admissible programs, the best (optimal) program (plan) is chosen according to the accepted criteria and optimality indices [13].**

3.2.1. Dynamic model of program control of MCO

$$M_o = \{\mathbf{u}^{(o)}(t) \mid \dot{x}_{i\gamma}^{(o)} = \sum_{j=1}^{m} \varepsilon_{ij}(t) \cdot u_{i\gamma j}^{(o)};\ x_{i\gamma}^{(o)}(t_0) = 0,$$
$$x_{i\gamma}^{(o)}(t_f) = a_{i\gamma}^{(o)},\ \sum_{i=1}^{m}\sum_{\gamma=1}^{s_i} u_{i\gamma j}^{(o)} \le c_j^{(o,1)},\ \sum_{j=1}^{m}\sum_{\gamma=1}^{s_j} u_{i\gamma j}^{(o)} \le c_i^{(o,2)},\ u_{i\gamma j}^{(o)}(t) \in \{0,1\},$$
$$u_{i\gamma j}^{(o)}\left[\sum_{\tilde{\alpha}\in\Gamma_{i\gamma 1}} (a_{i\tilde{\alpha}}^{(o)} - x_{i\tilde{\alpha}}^{(o)}) + \prod_{\tilde{\beta}\in\Gamma_{i\gamma 2}} (a_{i\tilde{\beta}}^{(o)} - x_{i\tilde{\beta}}^{(o)})\right] = 0,$$
$$i,j = 1,\ldots,m;\ i \ne j;\ \gamma = 1,\ldots,s_i\} \qquad (5)$$

- $x_{i\gamma}^{(o)}$: execution state of IO $D_{\gamma}^{(i)}$ (measurement, infocommunication or computing); $a_{i\gamma}^{(o)}$, $a_{i\tilde{\alpha}}^{(o)}$, $a_{i\tilde{\beta}}^{(o)}$: specified operation volumes
- $u_{i\gamma j}^{(o)}(t) = 1$ if operation $D_{\gamma}^{(i)}$ is executed, 0 otherwise; $\Gamma_{i\gamma 1}$, $\Gamma_{i\gamma 2}$: preceding operations linked by logical AND, OR
- $c_j^{(o,1)}$, $c_i^{(o,2)}$: technical constraints of satellite hardware-software complexes; $\varepsilon_{ij}(t) = 1$ if B_i is in the interaction zone of B_j, 0 otherwise

The matrix indicator function $\varepsilon_{ij}(t)$ defines scenarios of structural dynamics of the MSC.

Dynamic model of proactive accuracy planning

Kalman-Bucy filter model [17]

$$M_e = \{\mathbf{u}^{(e)}(t) \mid \dot{\mathbf{x}}_i^{(g)} = \mathbf{F}_i(t)\,\mathbf{x}_i^{(g)};\ \ y_j^{(i)}(t) = \mathbf{d}_j^T(t)\,\mathbf{x}_i^{(g)} + \xi_j^{(e)};$$

$$\dot{Z}_i = -\mathbf{Z}_i\mathbf{F}_i - \mathbf{F}_i^T\mathbf{Z}_i - \sum_{j=1}^{m}\sum_{\tilde{\gamma}\in\Gamma_i} u_{i\tilde{\gamma}j}^{(e)}\frac{\mathbf{d}_j\mathbf{d}_j^T}{\sigma_j^2}; \qquad (6)$$

$$i \neq j;\ \ i,j \in \tilde{M};\ \ 0 \le u_{i\tilde{\gamma}j}^{(e)} \le c_{j\tilde{\gamma}}^{(e)}\,u_{i\gamma j}^{(o)}\}$$

- $x_i^{(g)}$: state vector of service object $\bar{B_i}$; $F_i(t)$: dynamics matrix of measured parameters; $\xi_j^{(e)}$: uncorrelated Gaussian measurement errors with zero mean and variance σ_j^2
- $u_{i\tilde{\gamma}j}^{(e)}(t)$: intensity of measuring parameters $y_j^{(i)}(t)$ of a service object by satellite B_j; $d_j(t)$: measurement equation vector of satellite B_j
- Z_i: inverse of the correlation matrix $K_i(t)$ of state estimation errors of service object $\bar{B_i}$

Through constraints on $u_{i\tilde{\gamma}j}^{(e)}$, measurements are tied directly to satellite MCO: MCO and measurements are planned from a single system standpoint.

Objective functions of proactive MCO planning

$$J_1^{(o)} = \frac{1}{2}\sum_{i=1}^{m}\sum_{\gamma=1}^{s_i}\{[a_{i\gamma}^{(o)} - x_{i\gamma}^{(o)}(t_f)]^2 + \sum_{j=1}^{m}\int_{t_0}^{t_f}\eta_{i\gamma}(\tau)\,u_{i\gamma j}^{(o)}(\tau)\,d\tau\}, \quad i \neq j; \tag{7}$$

$$J_2^{(e)} = \vec{b}_\gamma^{\,T}\,\mathbf{K}_i(t_f)\,\vec{b}_\gamma;$$

$$J_3^{(e)} = \sum_{i=1}^{m}\sum_{j=1}^{m}\sum_{\tilde{\gamma}\in D^{(i)}}\int_{t_0}^{t_f} u_{i\tilde{\gamma}j}^{(e)}(\tau)\,d\tau, \quad j \neq i, \tag{8}$$

- $\eta_{i\gamma}(\tau)$: known monotonic functions of time chosen according to the start (end) deadlines of IO between service objects and the MSC
- index (7): completeness of meeting the boundary conditions and the total penalty for missed deadlines
- accuracy index of the χ-th component of $x_i^{(g)}$; $\vec{b}_\chi = ||00\ldots1\ldots00||^T$ selects element χ of the correlation matrix $K_i(t)$
- objective function of the total resource cost of the cyber-physical system for operations $D_{\tilde{\gamma}}^{(i)}$ that measure the state of service objects

3.2.2. Model of executing the measurement plan

Variational interpretation of the least squares method proposed by Prof. V. I. Mironov [17]

(9) $\bar{y}(t_q) = \bar{\psi}[\bar{x}(t_q)] + \bar{\delta}_q, \qquad q = 1, \ldots, N$ — model of actual observations

(10) $I = \sum_{q=1}^{N} \rho_q(\bar{y}(t_q), \bar{\psi}[\bar{x}(t_q)], \bar{\alpha}_q), \quad \rho_q = \ln f_q(\bar{y}(t_q) - \bar{\psi}[\bar{x}(t_q)], \bar{\alpha}_q)$ — maximum likelihood functional

(11) $\vec{\lambda}_i^{(g)}[t+1] = \vec{\lambda}_i^{(g)}[t] - F_i^T[t] \cdot \vec{\lambda}_i^{(g)}[t]$ — adjoint system of equations

(12) $\vec{\lambda}^{(g)}[t_q^+] = \vec{\lambda}^{(g)}[t_q^-] + \vec{d}_j^T \cdot K_i[t] \cdot \left[y_j^{(i)} - \vec{d}_j^T \cdot x_i^{(g)}[t_q] \right]$ — jump condition at time t_q of the current measurement

(13) $\vec{\lambda}[0] = \vec{\lambda}[T] = 0$ — boundary conditions of the adjoint system

(14) $\hat{x}_0 = \arg\min_{\bar{x}_0} I(\bar{x}_0)$ — estimation rule for the initial state of a service object

$\bar{y}(t_q)$: vector of actual (or simulated) measurements; $\bar{\psi}$: model measurement function; $\bar{\delta}_q$: measurement error vector; N: number of measurements.
Relations (11)-(13) follow from the variational interpretation and L. S. Pontryagin's maximum principle.

3.2.3. Inter-model coordination of measurement planning and execution

$$K_i^{(pl)}[t] = \left(Z_i^{(pl)}[t]\right)^{-1} \quad (15)$$

$$K_i^{(real)}[t] = \left(Z_i^{(real)}[t]\right)^{-1} \quad (16)$$

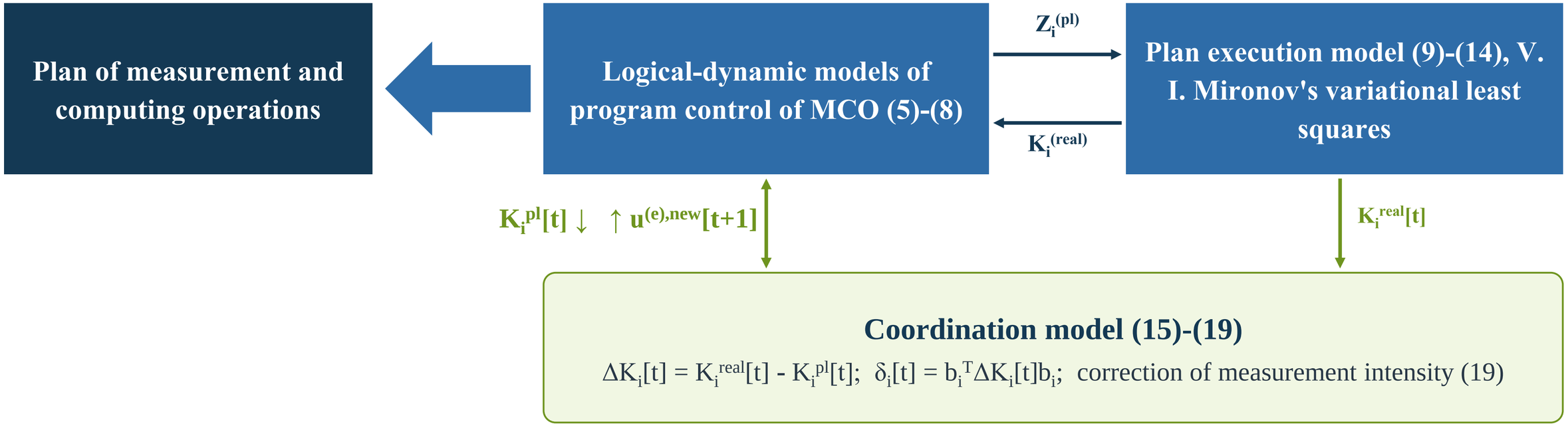
$$\Delta \mathbf{K}_i[t] = \mathbf{K}_i^{real}[t] - \mathbf{K}_i^{pl}[t] \quad (17)$$

$$\delta_i[t] = b_i^T \, \Delta \mathbf{K}_i[t] \, b_i \quad (18)$$

$$\mathbf{u}_{i\gamma j}^{(e),new}[t+1] = \Pi[0,\ c_{j\gamma}^{(e)} \, \mathbf{u}_{i\gamma j}^{(o)}[t]] \, (u_{i\gamma j}^{(e),pl}[t] + \kappa_{i\gamma j} \, b_i^T \, \Delta \mathbf{K}_i[t] \, b_i) \quad (19)$$

- $K_i^{pl}[t]$, $Z_i^{pl}[t]$: planned error matrix and information matrix (model (6)); $K_i^{real}[t]$: actual error matrix (model (12)); $Z_i^{real}[t]$: actual information matrix
- $\Delta K_i[t]$ characterises the mismatch between actual and planned accuracy and is used for feedback controls
- $\delta_i[t] > 0$: the actual error exceeds the planned one, the MCO plan should be reinforced with additional measurements [17, 18]
- the projection operator Π keeps the constraints of model (6); $b_i^T \Delta K_i[t] b_i$ selects the controlled error component

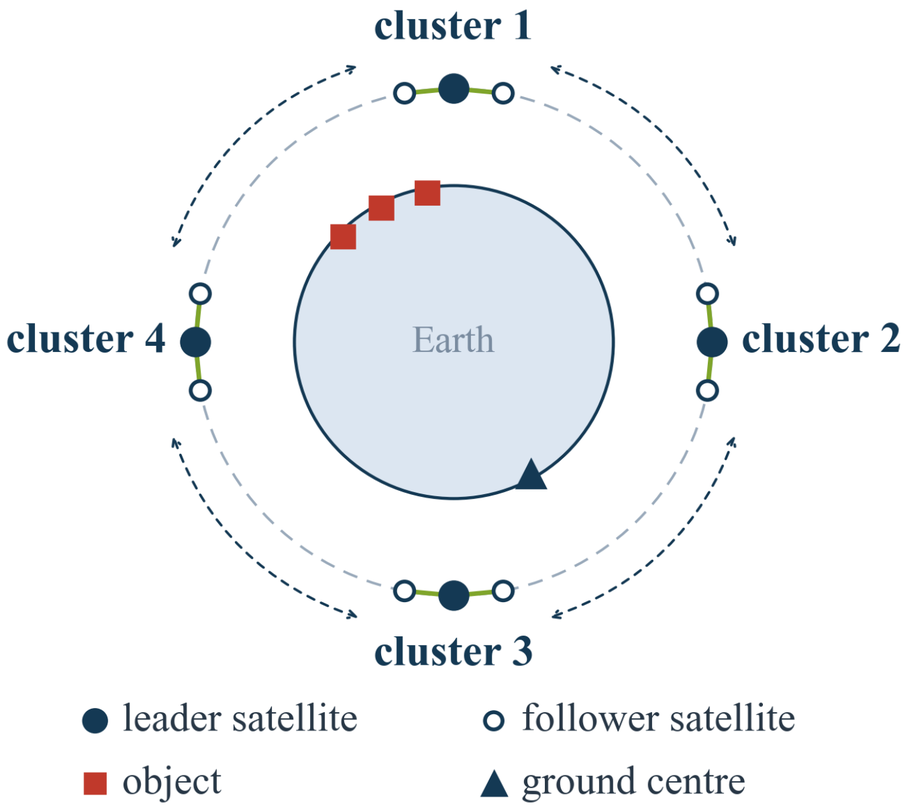
Model-based and algorithmic support and the computational procedure



At each horizon step: synthesis of the plan and measurement intensities → execution and assessment → compensation of $\Delta K_i[t]$ by plan correction or transition to the next step.

4. Results

4.1. Initial data

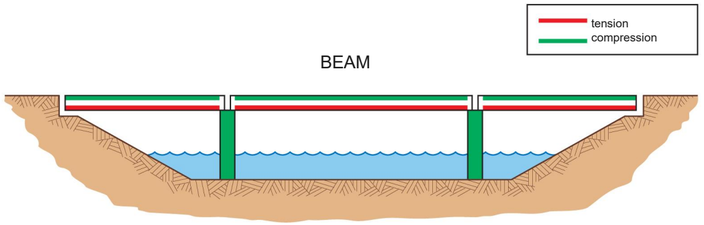


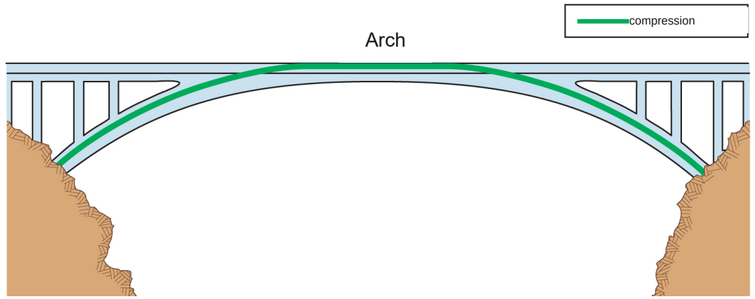
Parameter	Value
Service objects	bridge A, bridge B, bridge C
MSC	12 observation satellites in one plane
Orbit	circular, low altitude, 400 km
Clusters	4; one leader and two followers [18]
Modes	scheduled, reactive and proactive
Horizon / step	7 days / 1 hour

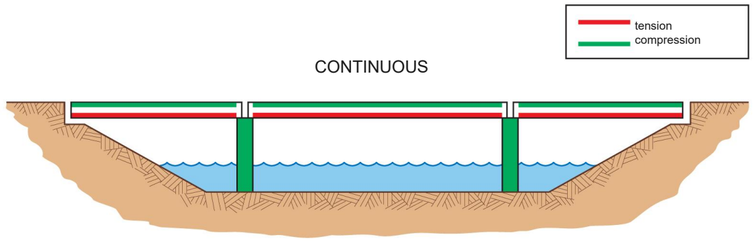
Goal: to demonstrate the effect of proactivity on quality indices.

Analytical-simulation model; the numerical values are for demonstration and are to be replaced by real telemetry data.

4.1. Initial data: observed objects







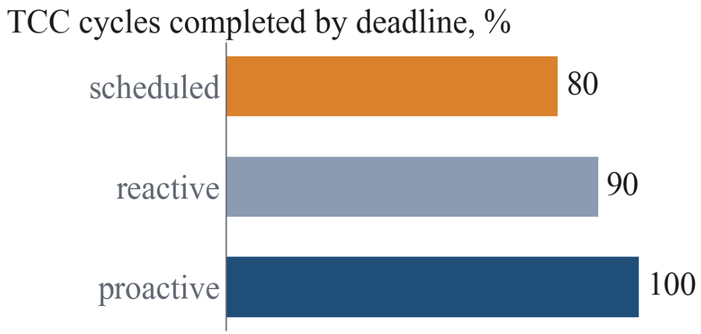
Parameter	Bridge A	Bridge B	Bridge C
Superstructure type	beam	continuous	arch
Natural frequencies of modes 1 / 2 / 3, Hz	3.0 / 5.5 / 9.0	2.2 / 4.0 / 6.8	3.5 / 6.0 / 10.0
State over 7 days	intact	damage develops from day 2: the mode 1 frequency drops by 0.066 Hz (3.0%)	intact
TCC (technological control cycle) for each bridge	every 8 h: measurement 2 h in a satellite interaction window → onboard processing 1 h; deadline: start of the next cycle		
Required frequency estimation accuracy	±0.008-0.014 Hz (two single-measurement errors)		

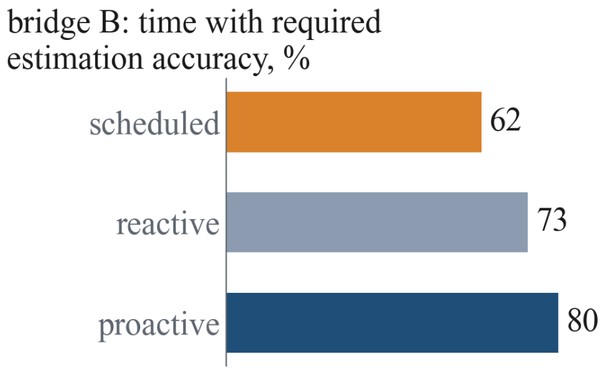
On days 4-5 one satellite cluster is re-tasked: interaction windows become shorter and shared by the three bridges. All strategies have the same resource: one measurement operation and one processing operation per hour. Measurement errors are calibrated on the KW51 field dataset; 30 noise realisations.

4.2. Results: TCC operations and estimation accuracy

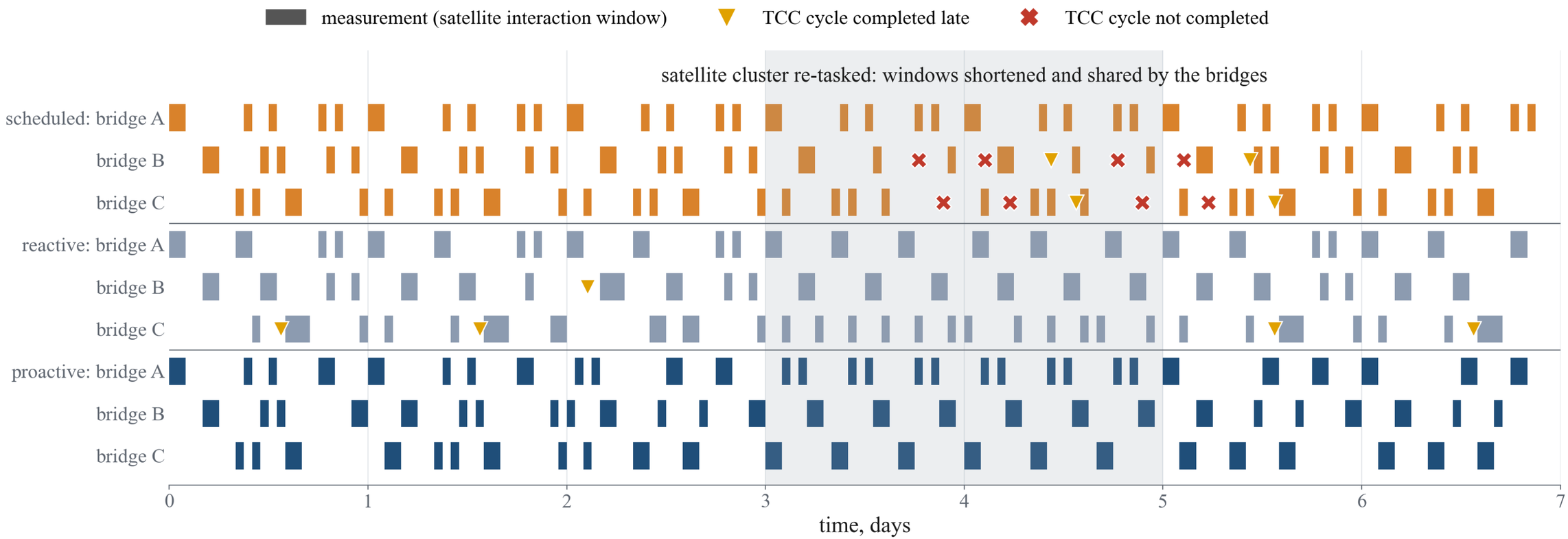
Index	Scheduled	Reactive	Proactive
TCC cycles (of 61): on time / late / not completed - index (7)	49 / 4 / 8	55 / 6 / 0	**61 / 0 / 0**
Measurement operations: performed (failed) - resource cost (8)	114 (8)	122 (0)	**122 (0)**
Time with required estimation accuracy, %: bridges A and C - index (8)	100	100	**100**
Time with required estimation accuracy, %: bridge B after damage onset	62	73	**80**

With the same resource, only the proactive strategy completes all TCC cycles on time and keeps the required estimation accuracy for the damaged bridge longest. Mean over 30 realisations.





4.2. Results: allocation of TCC operations by strategy



- scheduled: the timetable is fixed in advance and not rebuilt - when the cluster is re-tasked, measurements fall into closed windows and cycles are lost;
- reactive: serves the bridge with the largest error without regard to deadlines - some cycles are late;
- proactive: plan based on the forecast of windows and deadlines, coordinated with the actual accuracy (15)-(19) - all cycles are on time.

4.2. Overall results

- The proactive approach needs slightly more enhanced observations than the reactive one: about two to four extra sessions per week with a free measurement budget.
- Periods when the required accuracy is not reached and the false alarm rate are substantially reduced; with a fixed budget the same effect comes from redistribution.
- The ranking of strategies holds at every load level, for every source and for every period of real recording.
- The assessment refers to the analytical-simulation logical-dynamic level of the complex for one constellation configuration; the neuro-symbolic and multi-agent components were used only in the proactive strategy, and their separate assessment is ongoing work.

Discussion

Main idea: a dynamic interpretation of space computing control problems as problems of multi-criteria, poly-model, multi-level and multi-stage flexible situational allocation of information-control and infocommunication system and individual resources of the MSC.

- Variants of the space Internet of Things are being created by different countries (USA, China, etc.) and resemble the terrestrial Industrial Internet of Things.
- Earlier results in systems cybernetics [12-15] are applied to proactive monitoring and control of space-based IIoT with a three-tier edge-fog-cloud architecture.

Conclusion

- The approach to synthesising technologies and programs for controlling information processes in the Industrial Internet of Things is transformed to distributed space measurements and computations.
- The dynamic interpretation of MCO of the MSC control cycles substantially reduces the dimensionality of planning problems and the connectivity of the algorithm; the dimensionality is set by the number of independent paths in the generalised network schedule and by current constraints.
- The control technology of MSC elements and subsystems is explicitly linked to the results of instrument complexes and to the characteristics of the MSC hardware-software complexes.

Rational (optimal) MSC planning:

- increases the throughput of the MSC as a whole;
- reduces resource costs of MCO and delays in control loops;
- lowers the risk of peak information loads under sudden changes of the MSC structure.

Outlook: substantiated requirements for MSC hardware-software complexes, e.g. for the parameters of the navigation field. Practical implementations: http://litsam.ru

Monographs of the authors' team



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Thank you for your attention!

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