Supplementary File for Paper: Temporal Mission Planning of Autonomous Avoidance for Spacecraft Confronting Orbital Threats: An Interval-based Heuristic Approach

To enhance the clarity and comprehensibility of our proposed approach, we have included additional graphical formulas and concrete examples highlighting the core innovations. Specifically, **we provide a detailed illustrative explanation using two representative subsystems considered in this paper, including the servo turntable and the microwave radar.** In the planning model presented in this paper, these two subsystems are not only subject to internal constraints but also interact with other subsystems of the spacecraft. However, **for the sake of clarity and ease of understanding, we focus exclusively on the internal constraints within these two subsystems and the constraints arising from their mutual interactions.** The constraints involving other subsystems are temporarily omitted in this explanation to provide a more concise and illustrative example. These examples demonstrate how the subsystems are modeled within the planning framework, how the relaxed planning graph (RPG) is extended, and how the associated annotating functions are defined within the RPG. Through these detailed examples, we aim to make the proposed planning strategy more transparent and interpretable for the reader.

(1) In the planning model of this paper, the problem of mission planning is characterized by a five tuple $\Sigma = \langle \mathcal{P}, \mathcal{V}, \mathcal{I}, \mathcal{G}, \mathcal{A} \rangle$, where $\mathcal{P}$ denotes the set of states that is the Boolean propositions; $\mathcal{V}$ denotes the set of involved resources; $\mathcal{I} \subset \mathcal{P} \cup \mathcal{V}$ describes the initial state; $\mathcal{G} \subset \mathcal{P} \cup \mathcal{V}$ indicates the state of the goal; $\mathcal{A}$ depicts the set of durative actions.

An action $\alpha \in \mathcal{A}$ is a tuple as $\alpha = \langle \mathcal{D}, \mathsf{Pr}_{\triangleright}, \mathsf{Pr}_{\bowtie}, \mathsf{Pr}_{\triangleleft}, \mathsf{Ef}_{\triangleright}, \mathsf{Ef}_{\triangleleft}, \mathcal{F} \rangle$, where $\mathcal{D}(\alpha)$ is the duration of the action; $\mathsf{Pr}_{\triangleright}(\alpha)$ is the precondition of the action; $\mathsf{Pr}_{\bowtie}(\alpha)$ represents the invariant condition; $\mathsf{Pr}_{\triangleleft}(\alpha)$ denotes the end condition of an action; $\mathsf{Ef}_{\triangleright}(\alpha)$ is the start effect of an action; $\mathsf{Ef}_{\triangleleft}(\alpha)$ is the end effect; $\mathcal{F}(\alpha)$ is flexible parameters (FPs) defined in the action. In an action, if the conditions and effects $\{\mathsf{Pr}_{\triangleright}, \mathsf{Pr}_{\bowtie}, \mathsf{Pr}_{\triangleleft}, \mathsf{Ef}_{\triangleright}, \mathsf{Ef}_{\triangleleft}\}$ are the propositions of states, $\{\mathsf{Pr}_{\triangleright}, \mathsf{Pr}_{\bowtie}, \mathsf{Pr}_{\triangleleft}, \mathsf{Ef}_{\triangleright}, \mathsf{Ef}_{\triangleleft}\} \in \mathcal{P}$. If the conditions and effects $\{\mathsf{Pr}_{\triangleright}, \mathsf{Pr}_{\bowtie}, \mathsf{Pr}_{\triangleleft}, \mathsf{Ef}_{\triangleright}, \mathsf{Ef}_{\triangleleft}\}$ involves resource variables, $\{\mathsf{Pr}_{\triangleright}, \mathsf{Pr}_{\bowtie}, \mathsf{Pr}_{\triangleleft}, \mathsf{Ef}_{\triangleright}, \mathsf{Ef}_{\triangleleft}\} \in \mathcal{V}$.

To clarify the meaning of each element in the planning model, we provide a detailed explanation using the subsystems of servo turntable and microwave radar. After a space target is detected, the microwave radar used to distance measurement are driven by a two-dimensional servo turntable to achieve dynamic scanning and sensing of space targets. **The execution sequence of the two subsystems is as follows: the servo turntable is first opened. Then, the turn, calibration, and alignment are performed toward the target. Once the turntable has successfully aligned with the target, the microwave radar can then proceed to collect the target information.** Some constraints are represented by elements of the planning model as shown in Table I. The symbols and annotations in Table I are explained in Table II. **From Table I and Table II, we demonstrate how each element of the model, including actions, preconditions, effects, time and resource constraints, and FPs, is instantiated in these two subsystems. Through this concrete example, the roles and semantics of each element in model can be clearly understood in terms of specific behaviors of subsystems and their mutual interactions within the planning framework.**

TABLE I

SOME CONSTRAINTS REPRESENTED BY ELEMENTS IN THE PLANNING MODEL

Subsystems	Microwave radar			Servo turntable				
Actions	Open	Scan	Close	Open	Turn	Calibrate	Alignment	Close
$\mathcal{D}(\alpha)$	3	11-13	1	2	$\mathcal{F}$	4	2	1
$\mathsf{Pr}_{\triangleright}$	$avail$, can_open	$aligned$	$micro\_on$	$avail$, $\mathcal{F}$	$servo\_on$	$pointed$	$calib$	$servo\_on$
$\mathsf{Pr}_{\bowtie}$	$pow > 2$	$micro\_on$	/	$pow > 2$	$pow > 26$	$servo\_on$	$servo\_on$	/
$\mathsf{Pr}_{\triangleleft}$	$\mathcal{D} > 3$	$\mathcal{D} > 11$	/	$\mathcal{D} > 2$	/	$\mathcal{D} > 4$	$\mathcal{D} > 2$	/
$\mathsf{Ef}_{\triangleright}$	dec_pow	dec_pow	/	dec_pow, $\mathcal{F}$	dec_an	dec_pow	dec_pow	/
$\mathsf{Ef}_{\triangleleft}$	$micro\_on$	$infor$	off	$servo\_on$	$pointed$	$calib$, can_open	$aligned$	off

(2) Building upon the above example, we further elaborate on how the RPG is extended and how the annotating functions are defined to represent key variables in the involved subsystems. **The RPG includes the alternate fact layers and action layers, and the annotations are denoted by fl_i and al_i, $i = 0, 1, \cdots, n$, representing the i-th layer. The action layer includes the actions that are met in the previous fact layer. The fact layer includes the satisfied propositional facts in $\mathcal{P}$ and the bounds of resource variables in $\mathcal{V}$.**

It is assumed that the preconditions (i.e., $\mathsf{Pr}_{\triangleright} = avail$) of the turntable open are satisfied at

TABLE II

SYMBOLS AND ANNOTATIONS IN TABLE I

Symbols	Annotations
$avail$	The subsystem is currently available.
$pow > X$	The power resource needs to be greater than X, where X is a numeric value.
$\mathcal{D} > X$	The duration needs to be greater than X seconds, where X is a numeric value.
dec_pow	The capacities of power resources are decreased.
dec_an	Turntable rotation reduces the angular deviation between the sensor and the target.
can_open	Other sensors can be switched on.
off	The subsystem has been shut down.
$micro\_on$	Microwave radar has been switched on.
$servo\_on$	Servo turntable has been switched on.
$aligned$	The device is already aligned with target.
$calib$	The device has been calibrated with the target.
$pointed$	The turntable is already pointing to the target.
$infor$	The sensor has collected the information of target.
$\mathcal{F}$	The duration is defined as FPs in turn action, and the allocation of storage resources is defined as the FPs in the open action of turntable.

the fact layer fl_1. Then, the RPG is subsequently expanded forward. A local RPG constructed based on the two subsystems of microwave radar and servo turntable is illustrated in Fig. 1. The red lines indicate the graph expansion associated with the two example subsystems. p and act represent other propositions and actions in the corresponding layers that are unrelated to these two subsystems.

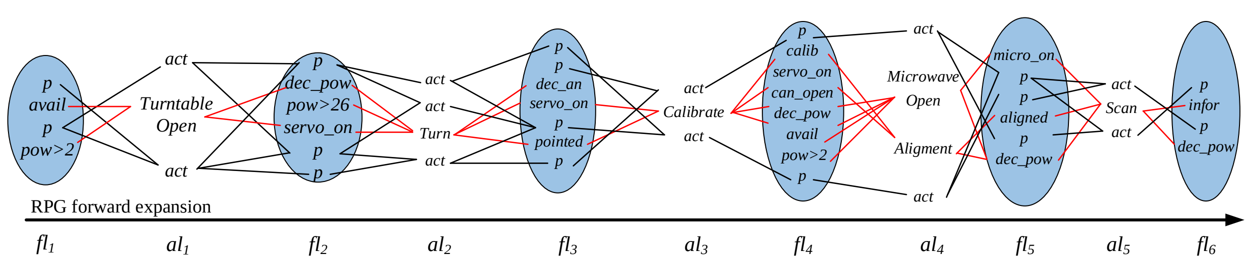

Fig. 1. A local RPG constructed based on the microwave radar and servo turntable.

(3) The following functions are adopted to annotate the information in RPG, and we use

Fig. 1 to explain the meanings of each function.

- $\Gamma(\mathsf{p})$: The fact layer of the RPG is recorded, where the fact $\mathsf{p} \in \mathcal{P}$ is first added. **For example, the proposition** $servo\_on$ **is first added in** fl_2 **of the RPG, so** fl_2 **is recorded in the annotation function** $\Gamma(servo\_on)$**. Similarly,** can_open **in** fl_4 **is first added in RPG, and thus** fl_4 **is recorded in** $\Gamma(can\_open)$**.**
- $\Upsilon(\nu, \mathcal{C}r)$: For a resource variable $\nu \in \mathcal{V}$ and a condition of resource $\mathcal{C}r$, the bounds of interval on ν are calculated by $\Upsilon(\nu, \mathcal{C}r)$ to satisfy the condition. **For example, in the fact layer** fl_2**, let** ν **denote the power resource, and let** $\mathcal{C}r$ **be expressed as** $pow > 26$**. The capacity of power is consumed through the effect** dec_pow **in this fact layer. The function** $\Upsilon(\nu, \mathcal{C}r)$ **is used to calculate the bounds of power resource after the application of** dec_pow**, where the computed bounds are used to evaluate whether the condition** $pow > 26$ **is satisfied. Likewise, in** fl_4**,** $\Upsilon(\nu, \mathcal{C}r)$ **calculates the bounds of power to determine whether condition** $pow > 2$ **is satisfied.**
- $\Lambda(\nu, \mathbb{B}, \mathsf{l})$: For a ν, a bound of the interval is denoted as $\mathbb{B}$. The index of a fact layer is represented as l. The lower or upper bounds of ν are last modified in the layer preceding fl_{l}, where the index of the preceding layer is returned by $\Lambda(\nu, \mathbb{B}, \mathsf{l})$. **For example, let** ν **denote the power resource, and the index of a fact layer is given as** $\mathsf{l} = 6$**. The last modification to the bounds of power before** fl_6 **occurs in** fl_5**. Therefore,** $\Lambda(\nu, \mathbb{B}, \mathsf{l})$ **returns the fact layer** fl_5**, and the bounds of the power resource in** fl_5 **are recorded in** $\mathbb{B}$**.**

We hope that these additions provide a clearer and more intuitive understanding of the proposed RPG-based method. Considering the page limit of the paper and the need to maintain textual coherence, the above examples and explanations have been organized into this supplementary document.