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Human-Computer Interaction Design of Remote Control System for Automobile Crane Based on FBS

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Abstract:

Objective: To derive the user interaction paradigm and prototype design in the remote control process through human-computer interaction analysis and the FBS design model, construct the human-computer interaction process of the remote control system, and form a design plan for the crane remote control system. *Methods:* Firstly, based on user research and experiments, the human-computer interaction characteristics of the existing crane control system were analyzed and studied, and a human-computer interaction model of the crane remote control system was constructed. Secondly, combining functional requirements and user behavior characteristics, and using the FBS (Function-Behavior-Structure) design analysis method, the structural composition of the crane remote interaction system was derived, and specific solutions were designed based on human-computer interaction research. Finally, Creo Manikin was used for ergonomic simulation analysis and verification. *Conclusion:* Through human-computer interaction analysis and the FBS design model, design factors were identified and a design plan was developed, forming a design plan for the crane remote control system. This has certain theoretical research significance and application value for the design and development of remote operating system products for construction machinery.

Keywords:

Remote control system
Human-computer interaction
FBS design model
Ergonomic simulation

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1. Introduction

The automotive crane is a relatively special mechanical equipment that holds a pivotal position in China's equipment manufacturing industry. However, accidents during lifting operations occur frequently, resulting in casualties and property losses. Remote-controlled cranes represent an operational mode that can reduce safety accidents, allowing operators to adjust to other positions conducive to work operations based on their actual situations. Currently, domestic research on related engineering machinery design still focuses on the technical structure of mechanical parts, while user-centered design research remains scarce, and product operation modes fail to meet user cognitive needs. Determining how to utilize user cognitive needs to construct interaction forms in remote control systems is key to optimizing the human-computer interaction process. In recent years, scholars have combined FBS theory with design theory, conducting extensive research in areas such as equipment conceptual design and interaction design. Gero *et al.* (2004) integrated the FBS model, treating design requirements, product functions, behaviors, and structures as a unified system for design [1]. Lu Manze *et al.* (2018) applied the FBS model and primitive model to enhance the operability of conceptual design in mechanical equipment [2]. Zhang Qing *et al.* (2018) believed that the improved FBS design model can obtain optimal solutions for user needs through natural interaction techniques [3].

The above cases, which combine the FBS model with design theory, provide some reference for the design of crane remote control systems. However, research specifically targeting crane remote control systems remains limited. Therefore, this study attempts to investigate crane remote control systems through human-computer interaction analysis and the FBS design model, aiming to capture system functional requirements, derive behavioral patterns for remote crane operation, and ultimately form the structural composition of the crane remote control system.

2. Design elements and process construction for the remote control system of automotive cranes

2.1. Design elements for the remote control system of automotive cranes

In the field of engineering machinery, equipment operation methods are highly complex, and equipment operators require strong professionalism. When designing and manufacturing with a user-centered approach, it is essential to prioritize the safe and efficient completion of engineering tasks. The operational mode of remotely controlled cranes differs significantly from traditional methods, primarily in terms of the nature of operational tasks, variations in the operational environment, and user characteristics.

The nature of crane operational tasks is unique. Cranes are primarily aimed at handling large and heavy materials. Their operational mode is characterized by a high degree of informatization, complexity, and coordination among multiple factors. Therefore, when remotely executing lifting tasks, the mode of information transmission in human-computer interaction is crucial to maximize operational safety and user response efficiency.

The task execution environment is unique. Compared to traditional operational forms, users need to pay more attention to site conditions and cargo status during remote operations. For simple tasks, operators can complete them without being on-site. For complex or hazardous tasks, operators can place the remote control system on-site to accomplish the lifting tasks.

The technical abilities of operators are unique. Personnel performing lifting operations must have received relevant skill training and obtained corresponding professional qualifications. They possess a high level of standardization and professionalism, are predominantly young and middle-aged, have strong receptive abilities, and possess a wealth of natural interaction experience. This allows them to quickly adapt to and familiarize themselves with new operational modes during remote operations.

2.2. Design process construction based on FBS and human-computer interaction

The FBS provides a comprehensive and refined theoretical framework for product design, and its unique top-down analysis strategy can be effectively applied in the initial conception stage of product design [4]. The FBS model can establish a structural mapping between user needs and product systems, analyze user behavior, and further derive the expected system structure to ensure the rationality of the design scheme [5]. Starting with product functions, the transformation of "function-behavior" and "behavior-structure" is achieved, ultimately leading to innovative system design [6]. Compared to traditional engineering machinery control methods, this study transforms user behavior into a user task model. Through human-computer interaction analysis, a human-computer interaction model for the remote control system is constructed. The FBS model is applied to derive the structural composition of the crane's remote interaction system, deduce product solutions, and finally use Creo Manikin for ergonomic simulation analysis and verification [7]. The design process is illustrated in **Figure 1**.

3. Design analysis of the remote control system for automotive cranes based on human-computer interaction theory and the FBS model

3.1. Construction of a human-computer interaction model for the crane remote control system

The task of this design is to deeply investigate the processes and behavior patterns of human-device interaction, optimize human-computer interaction design to meet specific user needs, and grasp their psychological and behavioral characteristics. The study explores a new crane control mode that differs from traditional control methods, aiming to establish an interactive bridge between the crane and the user and enhance the practicality, convenience, and comfort of the remote control system.

This article focuses on the "Xu XCT75" automotive crane as the research target, exploring the human-computer interaction design of its remote control system. When users operate traditional engineering equipment for work, the equipment provides feedback through information collection, and users observe the control environment simultaneously. In the remote operation mode, when the user manipulates the equipment, the environmental images and audio from the job site are fed back to the user through the device. If the user is at the job site, they can intuitively experience the on-site environment and sounds. In the remote operation mode, the system needs to provide more feedback information. By analyzing the work process at the lifting site, the study obtains a user task analysis model, capture a set of user needs, and records user behavior information through the entire process of text, images, and videos. After analysis and combining expert and user interviews, we derive a human-computer interaction model for traditional work methods. Based on this, the study develops a human-computer interaction model for the remote control system [8], as shown in **Figure 2**.

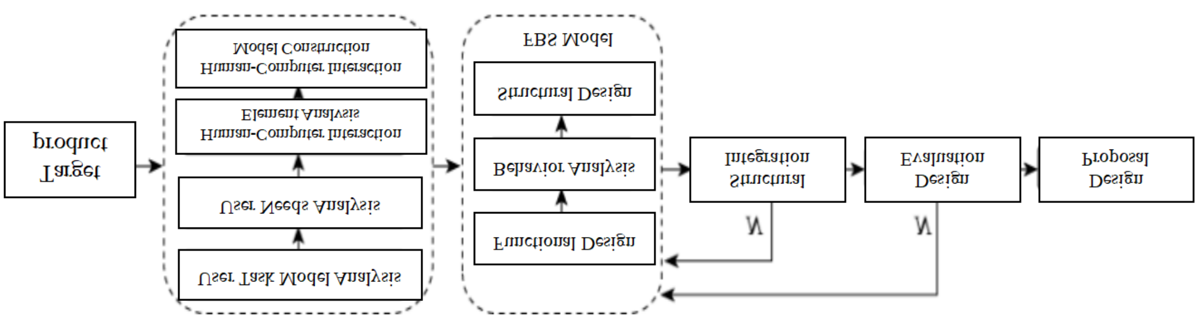

Figure 1. Design flow based on FBS design model.

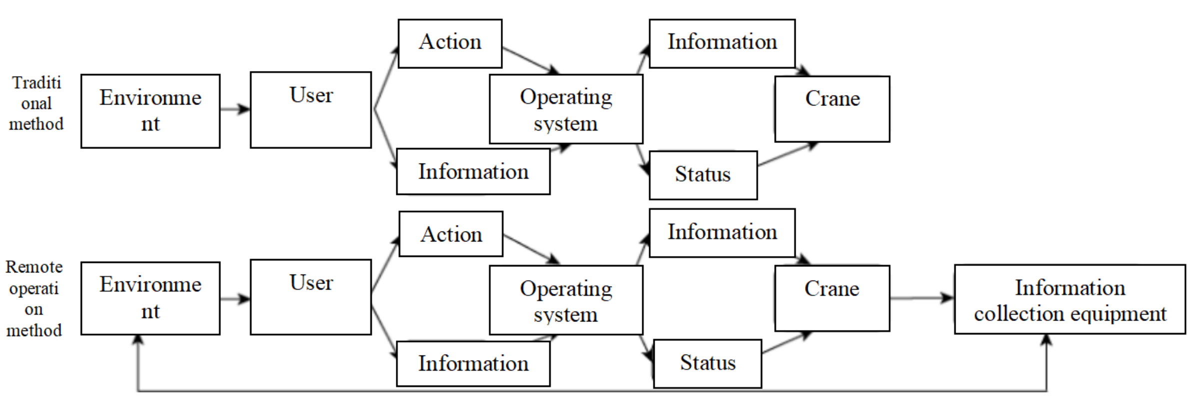

Figure 2. Human-computer interaction model.

3.2. Mapping transformation based on the FBS model

Through analysis of the user task analysis model and the human-computer interaction model, the operation process of the automotive crane is divided into a pre-work preparation stage and a work implementation stage, with emergency handling functions supporting the entire process. Before work activities, the operating system needs to be started, and the crane's status and parameters need to be preset. During work activities, the main operations include controlling the lifting and lowering of the hook, controlling extension, etc.

At the functional level, apart from traditional functions, the remote control system also needs to provide environmental monitoring and information feedback functions. At the behavioral level, to obtain environmental information on time, the traditional foot throttle control needs to be converted into a handheld operation mode. At the structural level, the remote control system requires functions such as a throttle knob and a hook monitoring display area, as shown in **Figure 3**.

Based on the FBS design model, the structure of the control system is analyzed, and the structural composition of the remote operating system is derived, as shown in **Figure 4**.

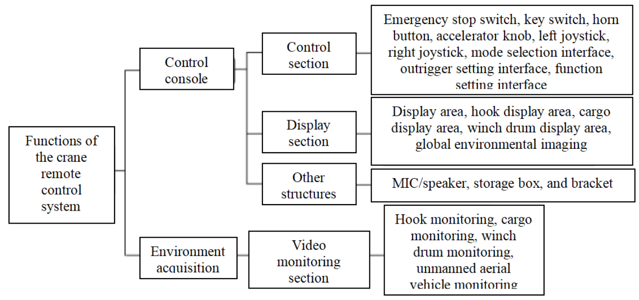

Figure 4. Structural components of remote control system for crane.

4. Design practice

4.1. Overall layout design of the crane remote control system

Based on human-computer interaction analysis, it is evident that both remote and traditional control methods

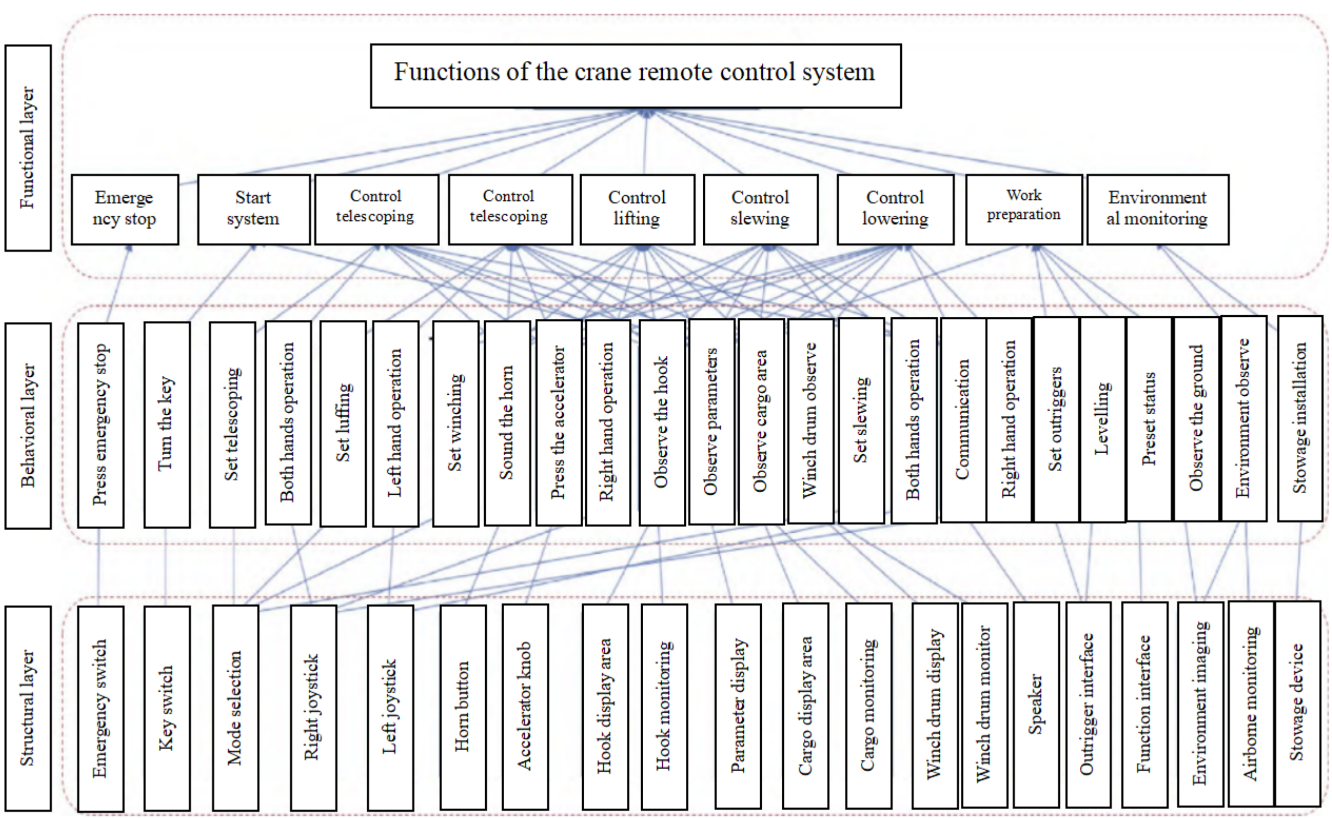

Figure 3. System design analysis based on FBS model.

require control handles with main functions such as rotation, extension, lifting, etc. The combination of two handles provides greater convenience. The horn function should be designed as a physical button to ensure safety during the entire operation. When subdividing the overall layout, principles of interface design and ergonomics should be considered. The interface layout should primarily adhere to safety principles, followed by frequency of use and sequence of use principles [9]. Incorporating feedback from users, engineers, and experts, the system layout can be divided into sections like the graphical interface interaction area and the work input area, as illustrated in **Figure 5**.

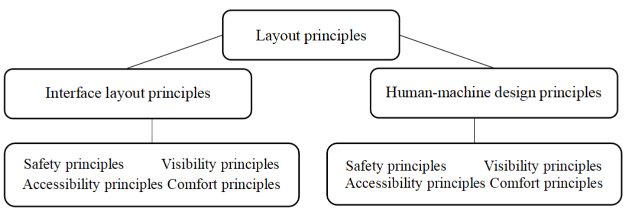

Figure 5. Overall layout principle.

Since preliminary preparations and the operational process do not need to be displayed simultaneously, they can be combined on the same screen, positioned in the upper-central part of the product. As users need to manually operate the outriggers, this function should be designed in a detachable form. The structural layout plan is shown in **Figure 6**.

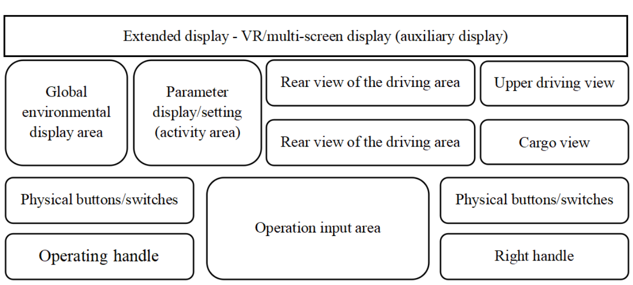

Figure 6. Structural layout scheme.

4.2. Research on the overall layout design and device dimensions of the crane remote control system

The control console should be designed as portable and compatible with both indoor and outdoor operations. Users can operate in a seated position during indoor tasks and in a standing position for specific outdoor scenarios. The screen, button positions, and dimensions of the control console should account for adult visual acuity and range of upper limb movement [10]. To meet the maximum visual distance requirements, this study selects the 95th percentile Chinese male body model as the subject for control console dimension research, as shown in **Figure 7**.

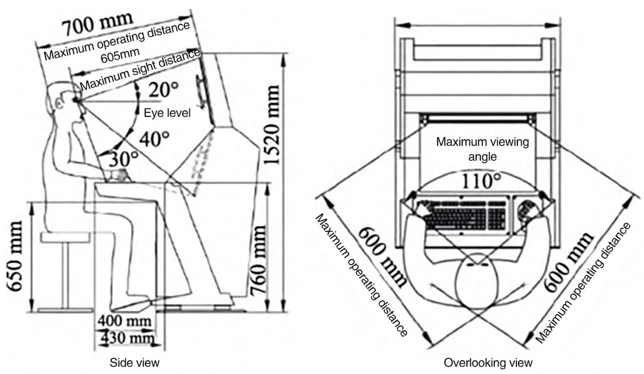

Figure 7. Size of the sitting console.

According to user research, the majority of crane users are young and middle-aged males. Ergonomic dimension research can refer to the Chinese standard "GJB 2873-1997" [11]. When seated, the desk height should exceed 650 mm, the display height should be less than 1520 mm, and a length of approximately 590 mm is considered comfortable. Typically, the horizontal field of view is 605 mm, with a comfortable visual angle ranging from 20° upward to 40° downward. Therefore, the width of the display group should not exceed 414 mm. Based on data analysis from "GJB 2873-1997" [12], the user's operational limit in the vertical plane is 700 mm, and the operational limit in the horizontal plane is 600 mm.

4.3. Design proposal for the main control console of the crane remote control system

The design proposal focuses primarily on the display screen and main structure, establishing the core of the control console. Generally, display screens can be fixed, foldable, detachable, etc., while the main structure can resemble a toolbox or laptop, among other options. After evaluation, the most suitable design combines a detachable screen with a laptop-style foldable structure, as shown in **Figure 8**.

Figure 8. Structural design scheme of the main console of a remote control system for crane.

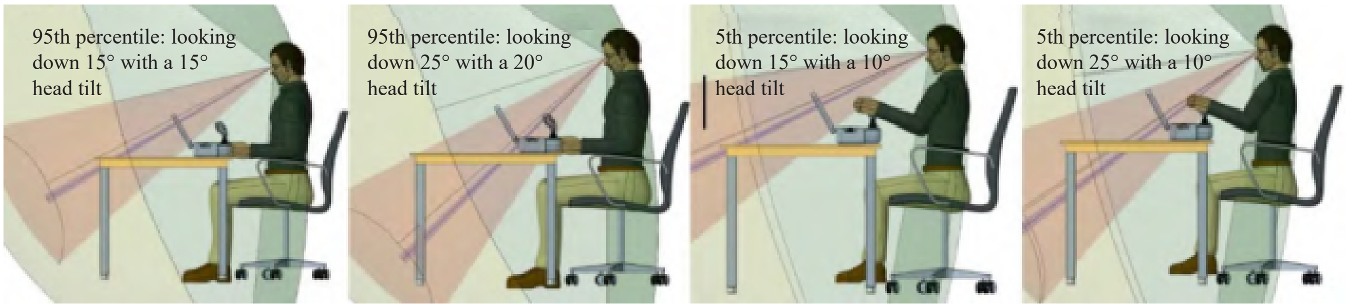

Figure 9. Visual field inspection results.

In the overall layout plan, the central display is dedicated to showing vehicle operational status and parameters, while the left and right displays monitor the work environment and vehicle conditions. Frequently used function buttons are centralized in the middle of the control console, with graphical icons and 1 to 3 indicator lights providing feedback. Physical switches like the horn and throttle are positioned on the dual handles for easy access. The control console display is designed as detachable, with a foldable main structure. The screen can function independently as a mobile device or be flipped for use with the control console. The recessed physical switches accommodate rotational operation, and the rotating handles can be stored in the toolbox.

5. Ergonomic simulation analysis of the design proposal

5.1. Establishment of the human body model

In the Manikin module of Creo 6.0, the human body model library includes 5th percentile, 50th percentile, and 95th percentile data from various countries [13]. Following the theoretical requirements of engineers, experts, and ergonomics, the basic human body model data for ergonomic simulation analysis in China is sourced from the "Chinese Adult Body Size" (GB10000-1988) in the Creo 6.0 module [14]. The model provides mean and standard deviation values for male body sizes in six regions of China [15], indicating that Northern Chinese males are slightly taller than the national average, but the difference is marginal. For ergonomic analysis, using the 5th and 95th percentile Chinese male body models is sufficient to cover the requirements of 90% of the population [16]. By matching these human models to the crane remote control console in operational mode, an ergonomic evaluation model for the control console is obtained.

5.2. Creo Manikin simulation analysis

Using Creo Manikin to simulate the field of vision (as shown in **Figure 9**), and adjusting the neck joint angle, it was found that the human eye can fully view the display screen when the head is lowered by 15° and the eyeball is looking down by 15°. When the head is lowered by 20° and the eyeball is looking down by 25°, the field of vision covers the display screen, handle, and physical buttons [17]. The ability to see all components on the control console within this range indicates that the field of vision meets the requirements.

The upper limb extension field directly affects workspace design and equipment placement. In Creo Manikin, the light blue area represents the reachable range of the upper limbs, and the physical buttons are all within this area, as shown in **Figure 10**.


(a) 95th percentile upper limb extension range (b) 5th percentile upper limb extension range

Figure 10. Analysis results of upper limb extension domain.

The posture evaluation module is the core of the human posture analysis submodule, capable of accurately evaluating human posture and providing a deep understanding of comfort and practicality. Compared to the upper limb evaluation in Creo Manikin, the posture evaluation module has a higher level of complexity in parameter setting, more detailed analysis results, and greater guidance value [18]. The joint torsion angles of the character model are divided into two levels: preferred and comfortable angles. When conducting posture evaluation, Creo Manikin calculates the final evaluation score based on the angles and values of each joint in the current posture [19], as shown in **Table 1** and **Table 2**.

According to the comfort analysis results and Figure 10, the comfort level of each joint is greater than 80%, indicating that the human body's rotation angles are within the comfortable range. Combining the analysis of field of view, upper limb extension range, and posture evaluation results, the design of this scheme meets the requirements of ergonomics.

Table 1. Comfort analysis results

Analysis content	95th percentile comfort analysis	5th percentile comfort analysis
Analysis documents	SAE_850484.mca	
The score of DOF has been displayed	112/140 (80%)	120/140 (85%)
Total score	112/140 (80%)	120/140 (85%)

Table 2. Detailed scores for comfort analysis

DOF	95th percentile comfort analysis	5th percentile comfort analysis
l_ankle-DOF1:	10/10	10/10
l_elbow-DOF1:	9/10	9/10
l_hip-DOF1:	8/10	8/10
l_knee-DOF1:	7/10	7/10
l_shoulder-DOF1:	7/10	7/10
l_wrist-DOF2:	10/10	10/10
r_ankle-DOF1:	10/10	10/10
r_elbow-DOF1:	9/10	9/10
r_hip-DOF1:	7/10	8/10
r_knee-DOF1:	7/10	7/10
r_shoulder-DOF1:	7/10	7/10
r_wrist-DOF2:	10/10	10/10
skullbase-DOF1:	8/10	9/10
vc7-DOF1:	9/10	9/10

5.3. Scheme optimization

New treatments have been applied to the corresponding positions of the horn button switch, emergency stop setting, throttle part, as well as the key opening and closing methods, to facilitate right-hand control. To ensure a compact and portable design, the original machine dimensions have been retained, and only the positions of the four switch components have been adjusted, as shown in **Figure 11**.

Figure 11. Effect diagram of the optimization scheme.

6. Conclusion

This article focuses on users and explores new research approaches for the system configuration, functional design, and human-computer interaction design of the crane remote control system through human-computer interaction design analysis. Starting from users' task requirements, user task models are established through methods such as video analysis and expert interviews, combined with the FBS design model. By utilizing the basic human body dimension data from "GB10000-1988," Creo Manikin is used to simulate the comfortable range of movement for the operator's upper arms, providing a design basis for the crane remote control device. Comprehensive evaluation opinions on human-computer interaction design are proposed, offering effective methods and approaches for improving human-computer interaction design.

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Disclosure statement

The authors declare no conflict of interest.

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