Proceedings on Automation in Medical Engineering
Proc AUTOMED, 2026, Vol. 3, No 1, Article ID 2532, 2 Pages

Phase-oriented feedback design for robotic scrub nurse handovers with contactless haptics

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Abstract: Instrument handovers between surgical staff and robotic scrub nurse (RSN) systems are safety-critical interactions under strong cognitive demands. While feedback modalities have been widely studied in human robot interaction (HRI) research, their systematic integration into the structure of handover processes in RSN systems remains less explored. This paper proposes a phase-oriented design framework for feedback in RSN handovers by decomposing the interaction into distinct phases and deriving modality-independent feedback requirements. Based on these, system-level design implications are discussed, including the role of contactless haptic feedback without a wearable device as a sterile, low-intrusion modality.

I. Introduction

Robotic scrub nurse (RSN) systems aim to support surgical teams by automating the handling and handover of surgical instruments [1,2]. Despite advances in perception and manipulation, instrument handovers in RSN systems remain a safety-critical and time-sensitive bottleneck, typically performed under strong visual demands. In human-human collaboration, handovers are coordinated through subtle cues such as motion timing and spatial positioning [3]. Replicating this fluency in RSN systems requires feedback mechanisms that communicate robot intent and state. In human robot interaction (HRI), communication is often realized through visual and auditory modalities [4], which may compete with visual attention or contribute to acoustic clutter in demanding environments. Haptic feedback has been proposed as an alternative or complementary channel [4-6], yet it is rarely considered in relation to the functional requirements of different handover phases. In this paper, it is proposed that feedback design for RSN handovers benefits from a phase-oriented perspective. We present a conceptual framework that decomposes the interaction into handover phases, assigns feedback functions to each phase, and discusses design implications, including the role of contactless haptic feedback.

II. Related Work

Research on RSN systems has demonstrated the technical feasibility of robotic instrument handling using various interaction paradigms, including speech, gestures, gaze-based input, and specialized grippers [1,2,7]. However, feedback to the human partner is typically limited to implicit robot motion or simple auditory cues. In the broader field of human-robot interaction, feedback has been studied using visual, auditory, and haptic modalities [4]. Visual feedback is effective but demands visual attention, which is limited in surgical contexts. Auditory feedback can convey state and timing information but may be perceived as intrusive in noisy environments. Haptic feedback has been shown to support intuitive interaction and reduce visual load, yet most implementations rely on wearable or contact-based devices [8]. Contactless haptic feedback based on focused ultrasound offers a promising alternative for sterile contexts without the need for a wearable device. However, its role in RSN handovers remains largely unexplored, particularly with respect to a structured mapping between handover phases and feedback functions.

III. Phase-Oriented Handover Model

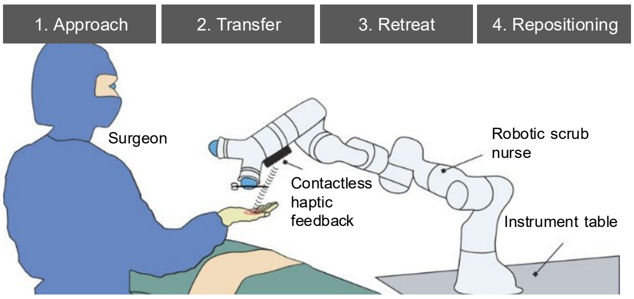

Figure 1: Schematic illustration of a surgeon receiving contactless mid-air haptic feedback during the delivery of an instrument and the four handover phases.

III.I. Decomposition of RSN Handovers

RSN instrument handovers can be conceptualized as a sequence of four phases, the order and occurrence of which may vary depending on the scenario (see Fig. 1). Prior to the initiation of these phases, the type of handover (instrument delivery or return) is defined.

Approach: RSN system moves toward anticipated handover location; the human partner benefits from awareness of robot motion and proximity.
Transfer: Robot reaches handover position, signals readiness to deliver/receive instrument, requests user action for acceptance; clear signaling ensures safe release/grasp, ambiguity can lead to hesitation or premature actions.
Retreat: After transfer, the robot retreats; predictable closure of the interaction supports trust and fluency.

Repositioning: In case of direct instrument exchange, the robot requests the user to wait while switching between its two grippers (see Fig. 1).

This decomposition highlights that RSN handovers are not monolithic actions but temporally structured processes with varying informational demands.

III.II. Feedback Functions Across Phases

Rather than assigning specific modalities to each phase, we derive modality-independent feedback functions:

Approach - Attention and spatial awareness: Indicating robot motion and proximity.
Transfer - State signaling: Communicating availability and timing for handover.
Retraction - Closure: Releasing the user's attention from the interaction.
Repositioning - Demand user responsibility: Indicating a robot action and a request for the human to wait during direct instrument exchange.

These functions provide a structure for feedback design that can be instantiated using different modalities depending on system constraints and context.

IV. System Design Considerations

IV.I. Design Requirements

From a phase-oriented perspective, several high-level design requirements for RSN handover feedback emerge: minimal visual demand to preserve focus on the surgical field, compatibility with sterile workflows without wearable devices, low cognitive load and intrusiveness through phase-relevant information, and temporal coupling to robot actions to support predictability and trust.

IV.II. Role of Contactless Haptics

Contactless haptic feedback aligns well with the design requirements of RSN handovers by supporting spatial awareness and state signaling without occupying visual or auditory channels. Its contactless nature ensures compatibility with sterile environments and eliminates the need for a wearable device. Within a multimodal feedback space, contactless haptics complement visual and auditory cues through subtle, localized signals, particularly suited for low-intrusion, eyes-free handovers.

IV.III. Exemplary System Instantiation

To illustrate the practical instantiation of the proposed framework, we consider an RSN system performing direct hand-to-hand instrument transfers. The handover phases are explicitly represented in the control logic and used to trigger phase-dependent feedback. A haptic unit mounted on the RSN projects spatial cues based on focused ultrasound into the handover space, for example onto the user's hand. This contactless haptic feedback serves as a complementary modality, providing localized, low-intrusion cues aligned with the temporal structure of the handover. Its contactless nature allows feedback to be perceived without visual attention. Fig. 2 illustrates an experimental setup utilizing the handover phases in the described RSN system.

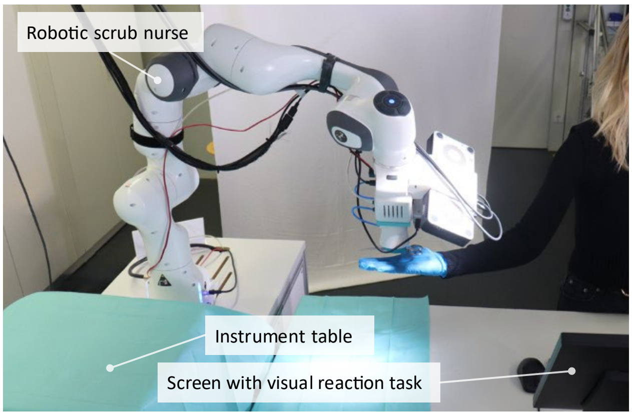

Figure 2: Experimental setup with participant interacting with the robotic scrub nurse system during bilateral hand-to-hand instrument transfers using auditory, haptic, and multimodal cues.

IV. Discussion and Outlook

The proposed phase-oriented framework structures feedback design for RSN handovers by shifting the focus from modalities to interaction functions, supporting systematic design choices and comparison across RSN implementations. Although this paper is conceptual and reports no empirical results, the framework provides a foundation for structured evaluation of feedback strategies. Future work will empirically assess feedback modalities and combinations across handover phases, focusing on subjective perception, safety, and cognitive load. Beyond RSN systems, the framework may also inform feedback design for other safety-critical human-robot handovers in medical and industrial contexts.

AUTHOR'S STATEMENT

Research funding: The authors state no funding involved. Conflict of interest: Authors state no conflict of interest. Informed consent: Not applicable. Ethical approval: Not applicable.

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