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A Dance Performance with a Humanoid Robot using a Real-time Gesture Responsive Framework

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Abstract— **We present a lightweight, real-time gesture responsive framework designed to investigate dynamics of human-robot interaction in live dance performances, merging aspects from choreography and robotics. In particular, it is tailored for artists to integrate human-sized humanoid robots into their dances seamlessly, offering an intuitive solution without the complexities of mastering robot control systems. Unlike existing interaction methods relying on wearable sensors or predetermined music cues, our framework, integrated in a task-space controller, enables the robot to dynamically respond to the dancer's movements, generating unpredictable yet artistically meaningful gestures without the need for body-mounted sensors. This design choice emphasizes the artistic intention behind the improvisation, illustrating that it is not merely about creating movements spontaneously but rather a way of expression in intuition guided by perception. We assess our framework on the HRP-4 humanoid robot and the result has been successfully demonstrated in a public human-robot dance performance at the Arts Center of Enghien-les-Bains's 23/24 season launch event, aiming to contribute to the exploration of co-creation between human and human-sized humanoid robot in improvised dance performances.**

I. Introduction

Human-robot interaction has evolved from rudimentary forms to autonomous behaviors, driven by advancements in artificial intelligence and sensor technologies. While these interactions find applications in healthcare, education, and industry, its integration into artistic realms, particularly with human-sized humanoid robots, remains relatively unexplored. Human-sized humanoid robots, characterized by their anthropomorphic design and dexterity, hold immense potential for fostering novel forms of expression and collaboration in artistic creation. Concurrently, modern dance has undergone a rebellion against classical ballet since the early 20th century [2], leading to a revolution in movement vocabulary. Figures such as Martha Graham [3], [4], Merce Cunningham [5], and Pina Bausch [6] have exemplified this shift, challenging rigid choreography through spontaneous determination [7] and dance-theatre methods Tanztheater [8]. Contemporary dance continues this experimentation and improvisation, incorporating a broader range of techniques from various dance forms, including non-western traditions, and tends to combine different mediums, such as multimedia installations, digital interface, and robots.

Dancing with robots has undergone extensive studies, exploring various forms of interactions [9], [10], as well as its effect under complex social settings [11]. Despite growing interest, the current landscape of improvised robotic dance performances is often limited by non-anthropomorphic robots, such as robotic arms, e.g., [12], crab, e.g., [13] or even mobile robots, e.g., [14]. Even when humanoid robots have been utilized in dance [15], [16] or artistic theatrical creations[1] they have often been smaller in scale rather than human-sized. However, pioneering research has demonstrated the dance capabilities of biped human-sized humanoid robots. For instance, HRP-2 has performed live dances following motion capture patterns [1]. Other human-sized robots, including Optimus-Gen 2, GR-1, Atlas, HRP-4C [17] and Kosaka, typically perform in predetermined scenarios, such as dancing in a hanging position[2] or synchronized movements with a group of robots[3,4]. Even in dance alongside humans, the emphasis often leans towards strict adherence to music rhythm[5,6], or imitating human dance motions [18], overlooking their potential for artistic co-creation with professional choreographers in contemporary dance.

Addressing these limitations, our research explores the concept of performance in a human-robot experimental stage space. The developed real-time gesture responsive framework showcases how a human-sized humanoid robot and a dancer combine their respective abilities to create movement and convey emotions, initiating a co-creative process in a cognitive domain, where understanding and emotion intertwine. To the best of our knowledge, it is the first time improvised artistic co-creation process is demonstrated with a human-sized humanoid robot HRP-4 in a public dance performance. The full controller executed during this performance is also open-sourced[7], aiming to make the creation of novel human-robot interaction performances more accessible to a wider community of artists.

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[1]www.lucyfestival.net/roboact
[2]www.youtube.com/watch?v=OgMXanULyRk
[3]www.youtube.com/watch?v=fn3KWM1kuAw\&t=18s
[4]www.youtube.com/watch?v=BvFxD-8AhJA
[5]www.youtube.com/watch?v=EoLhOnQNDCo
[6]www.youtube.com/watch?v=cpraXaw7dyc\&t=3s
[7]github.com/arntanguy/CDADance

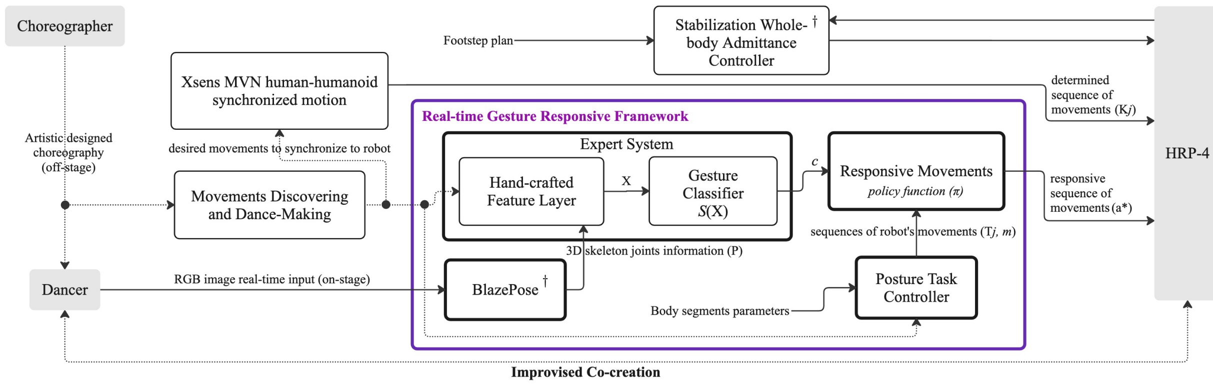

Fig. 1. The complete co-creation process of the public human-robot dance performance experimentation; the thick border represents the proposed real-time non-wearable gesture responsive framework; the superscript † refers to integrated models from previous work and the dotted line indicates the information designed by artists.

II. Problem Statement

A. Human-machine Improvisation

In the realm of human-machine interaction, the concept of interaction can be delineated into two paradigms: (i) the first interaction, and (ii) the second interaction [19], [20]. The former depicts machines as mere executors of pre-programmed rules, similar to marionettes controlled by puppeteers. In contrast, the latter signifies machines capable of self-evolution, adapting to their environment and exhibiting unpredictable behaviors. This hybrid relationship of the second interaction between humans and machines, mentioned in [21], plays a pivotal role in fostering responses based on personal experiences, thoughts, perceptions, and intuition, transcending mere adherence to instructions. It is within this context that improvisation and co-creation emerge as crucial components. By engaging in improvised interactions with machines, individuals are prompted to explore novel ways of expression and collaboration beyond traditional frameworks.

B. Choreography with Humanoid Robot

In the process of choreographing dance performances, collaboration between choreographers and dancers involves two main stages: movement discovery and dance-making process [22]. Movement discovery, led by dancers, entails attentive observation of inspiring elements like music, stage objects, or poetry. Choreographers then engage in an iterative process of evaluating, recreating, and integrating new dance movements. However, incorporating humanoid robots into choreography introduces complexity, primarily due to their unique physical characteristics and capabilities. A significant challenge is the design of a distinctive body language for humanoid robots, enabling them to fluently interpret observed gestures and integrate into improvisational interactions with dancers. In [23], an autonomous dance generation system for a small-sized humanoid robot has been discussed. Another system proposed by [24] also mediates the interaction between a musician and non-anthropomorphic bipedal robot. Additionally, the challenge of stabilization plays a critical role, as movements that may seem intuitive for human dancers, such as walking or raising a leg, present significant difficulties for humanoid robots. The stabilization of the HRP-4 humanoid robot has been researched extensively for various scenarios, including stair climbing, e.g., [25] and walking under a disturbances circumstances, e.g., [26].

C. Contribution

Our contribution to robotic artworks stands as follows:

- Successfully demonstrated in public an improvised human-robot dance performance with HRP-4 in an auditorium of 392 people, presenting co-creation process between artists and the robot.
- The developed real-time non-wearable gesture responsive framework highlights the creation of dynamic movements in interactions between dancers and robots. It aims at enriching artistic improvised co-creation processes with greater freedom and ease. The control framework architecture is shown in Fig. 1.

III. Real-time Gesture Responsive Framework

Fig. 1 illustrates the proposed real-time non-wearable gesture responsive framework, designed specifically for human-robot co-creative dance performance. The framework utilizes dancer's skeleton joint data as input, processed by an expert system informed by artistically designed movements for gesture classification. Additionally, a posture task (as part of the task-space quadratic program controller [27]) and responsive movements control are integrated to translate choreographer's dance-making sequences into robot's responsive movements. Finally, the execution is facilitated by integrating an extended stabilization whole-body admittance controller [25].

A. Gesture classifier

Given by the RGB real-time image sequence of the dancer captured by ZED 2 camera, the full 3D body pose is estimated by BlazePose [28]. The deployment of this estimation relies on the Mediapipe Pose [29] with *Full* model

TABLE I

NINE DESIGNED GESTURE CLASSES OF THE DANCER

Gesture Class	Semantic Meaning Designed by Choreographer	Class Name
1	Elation Ascendancy: indicates triumph, victory, or celebration.	right hand high-raising
2	Vigilant Salutation: represents readiness and attention.	right hand raising to the waist
3	Guiding Beacon: illuminates the path forward and signaling direction.	horizontally right hand raising
4	Aspiring Reverence: reflects reverence and aspiration for dreams.	left hand high-raising
5	Supportive Embrace: evokes support and nurturing.	left hand raising to the waist
6	Inclusive Invitation: indicates an open invitation, fostering inclusivity and engagement.	horizontally left hand raising
7	Curiosity's Lean: signifies curiosity and attentiveness	head tilted to right
8	Contemplative Pause: tilts in reflection, encouraging introspection.	head tilted to left
9	Unity: celebrate the shared joy	both hand high-raising

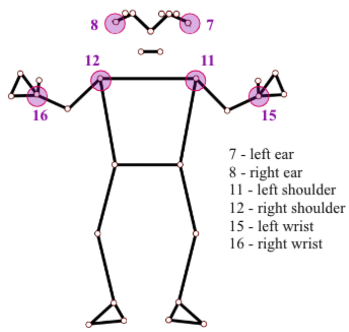

Fig. 2. The selected six 3D body pose position from the dancer.

bundle version selected. The detected body pose closest to the center of the screen and closest to the camera is chosen. If multiple individuals are present around the center of the screen, the person closest to the camera is selected based on the depth information obtained by the GHUM model [30]. Among the 33 estimated body landmarks, we selected position information from 6 landmarks only, due to their visibility when the camera (installed on the robot's head) move during the performance. These landmarks ensure the dancer's movements are reliably captured, even when the dancer is close to the robot. The indices of these landmarks are 7, 8, 11, 12, 15 and 16, as shown in Fig. 2 to be later used in gesture classifier. A total of nine gesture classes are defined, with semantic information provided in Table I.

The expert system consists of 9 different classifier models on top of one shared hand-crafted feature layer, incorporating semantic information of movement creation obtained from the choreographer. We note the input 3D skeleton joints information as P (body landmarks extracted by BlazePose), and its non-linear transformation features as D. Here, $P = (p_1, p_2, p_3, p_4, p_5, p_6)$, where each $p_i \in \mathbb{R}^3$ represents position information, with indices corresponding to selected body pose landmarks 7, 8, 11, 12, 15 and 16 respectively. $D = (d_1, d_2, d_3)$, where each d_i is the transform of raw position into distance, defined as:

$$d_1 = |p_{4,y} - p_{5,y}|, \; d_2 = |p_{3,y} - p_{4,y}|, \; d_3 = |p_{3,y} - p_{6,y}|$$

The P and D are then concatenated into combined feature $X = (P, D)$. Nine separate multilayer perceptron (MLP) models are applied to X, each applied with different activation function and returning the probability of a gesture class. The gesture classifier, denoted as $S(X)$, comprises an array of MLP for each gesture type: $[S_1(X), S_2(X), \dots, S_9(X)]$. The probability of each gesture, $S_i(X)$, is derived through a processing function that includes both linear and non-linear operations, defined as:

$$S_i(X) = \varphi_i(W_i \circ X + \beta_i)$$

where φ_i denotes the variant of ReLU, varying for each gesture; W_i is the parameters tailored to the i-th gesture; and β_i is a bias term adjusting the linear transformation's output before the application of the activation function. The final classification of the observed dancer's gesture c, is determined by selecting the gesture associated with the highest probability, defined as:

$$c = \arg\max_i S_i(X)$$

B. Responsive movements control

The responsive movements control defines a policy function to determine optimal artistic robot actions based on the observed dancer's gesture. The real-time input image of the dancer's gesture is interpreted into a discrete integer by the precedent gesture classifier, representing a class label within the range of $\{1, 2, \dots, 9\}$, defining the observation space $\mathbb{O}$. At given time t, each observation sequence is a sliding window of size 3 with step-size 2, denoted as (c_{t-2}, c_{t-1}, c_t), where $c_t == i$ is one-hot encoding of the class $i \in \mathbb{O}$. To effectively handle the streaming sequence of observed gestures, we further apply weighted average at each time t, denoted as:

$$\bar{c}_t = 0.2c_{t-2} + 0.3c_{t-1} + 0.5c_t$$

The action space $\mathbb{A}$ is defined as the Cartesian product of nine distinct movement sequence $j \in \{1, 2, \dots, 9\}$ of robots and two trajectory options, denoted as:

$$\mathbb{A} = \{(T_j, \mathrm{m}) \mid \mathrm{j} \in \{1, 2, \dots, 9\}, \mathrm{m} \in \{\text{BSpline}, \text{Exact Cubic spline}\}\},$$

where, T_j represents the robot's movement sequences designed by choreographer's dance-making process, shown in Fig. 3, and m denotes the trajectory option.

We then define a score matrix M, where each of its element $M_{i,j}$ represents the score of choosing action a_j in response to observation i. This score matrix quantifies the compatibility of each possible action with each observed gesture, guiding the selection of the optimal robot's movement response. We defined the policy function $\pi : \mathbb{O}^3 \rightarrow \mathbb{A}$ as:

$$\pi(\bar{c}_t) = a^* := \arg\max_{a_j \in \mathbb{A}} \ \bar{c}_t{}^T \circ M$$

where for each time step t, the optimal action a^* is determined by the highest action score of the weighted average observations $\bar{c}_t$.

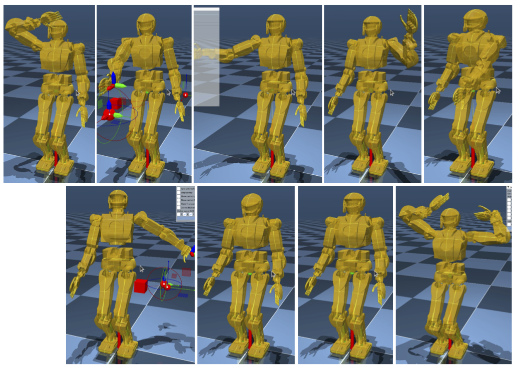

Fig. 3. Robot's movement sequences designed by choreographer's dance-making process. Sequentially depicted from left to right and top to bottom, representing T_1 through T_9 respectively.

IV. Experiments

In the following we first introduce our experimental environment, the additional human-humanoid synchronized motion controller integrated in the experiments, and finally the result of artistic improvised co-creation process between dancer and the humanoid robot HRP-4.

A. Experimental Challenges

The transition from controlled laboratory environments to live robotic performance experimentation on stage introduces a dynamic landscape with challenges in maintaining consistent experimental conditions. Unlike controlled settings, the stage environment is characterized by its variability, including lighting conditions and stage settings that are subject to continual changes based on artistic decisions made by individuals such as stage directors, choreographers, and dancers. Also, safety systems for the humanoid shall be redesigned to be as invisible as possible to the audience. Furthermore, the inherent fragility of human-sized humanoid robots, initially designed for robotic research targetting industrial applications rather than artistic dance purposes, presents significant challenges. Instances of mechanical malfunction, such as occasional falls during walking rehearsals with dancers, underscore the risks in executing a performance perfectly. Additionally, the extended duration of sustained robotic activity required for meticulous rehearsal and the execution of dance performances demands very careful considerations.

B. Experimental environment and settings

In the realm of this research, we designed an experimental stage space to present a 10-minute public human-robot dance performance at the Arts Center of Enghien-les-Bains's 2023/2024 season launch event. Collaborating closely with a stage director, we designed a performance stage characterized by four white boards positioned vertically at the center, within the expansive 250 m^2 stage area, shown in Fig. 4. These boards, measuring 3 m $\times$ 1.5 m and 3.5 m $\times$1.5 m respectively, were strategically incorporated to convey a narrative depicting a girl's initial encounter with a humanoid robot, and since the dance-movements carried out in this performance is followed by the Tanztheater approach [8], detailed theatrical dance script is also developed and described in the Appendix. The performance featured a single dancer and a HRP-4 humanoid robot, with lighting carefully arranged to complement each interaction between them. A total of 104 hours were dedicated to meticulously rehearsing on the stage, integrating dancer, robot, lighting, music, and scenography. Moreover, to ensure safety, the HRP-4 was secured with two 8 mm diameter steel ropes attached to the stage ceiling throughout the whole experimentation. Additionally, our real-time gesture responsive framework was carried out by a ZED 2 camera installed on the HRP-4, with video output configured to 720p mode and a resolution of 2560×720.

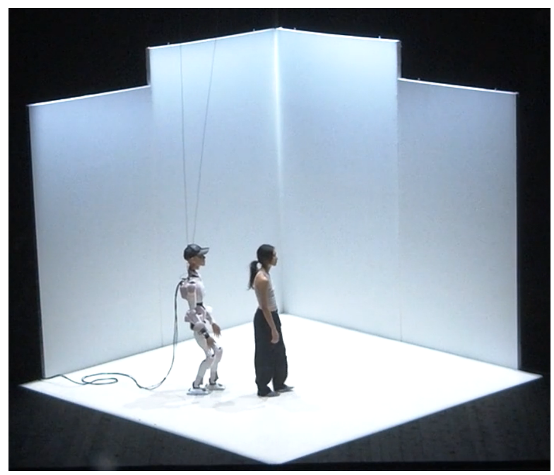

Fig. 4. The performance stage designed by stage director.

C. Human-humanoid synchronized motion

In addition to the interactive movements generated from real-time gesture responsive framework, this performance was composed of pre-determined sequence of robot's movements to complement the theatrical dance script. The complete co-creation process of this experimentation is shown in Fig. 1. To ensure the synchronization of aesthetic choreography, we integrated a motion capture retargeting controller, allowing for the direct creation of robot movement sequences derived from the dancer's movements recorded via a wearable device, thereby mitigating the labor-intensive process of manually configuring each movement using traditional posture tasks controllers. This human-humanoid motion synchrony method, inspired from [31], leverages low-lag human tracking technology[1] to create the translation of dancer

[1]www.xsens.com/motion-capture

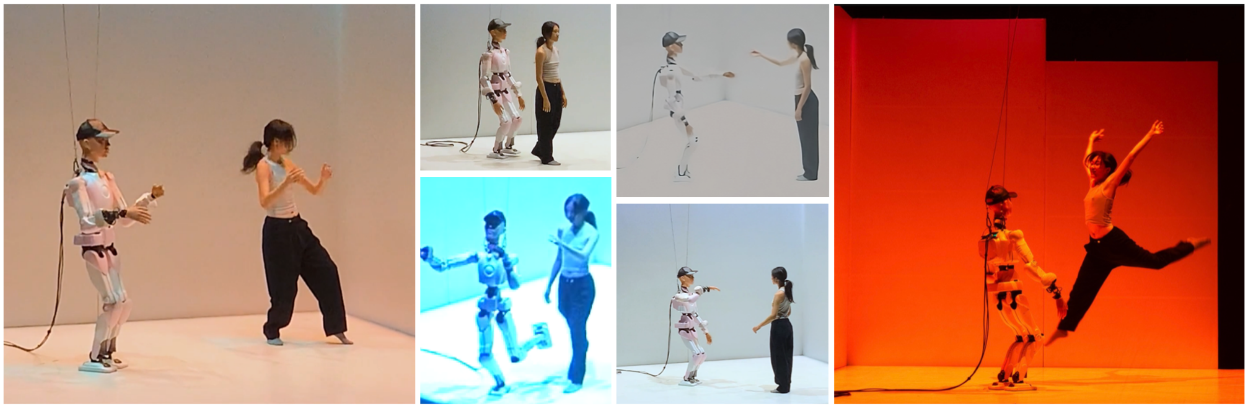

Fig. 5. The result of the live co-creation dance performance featuring a dancer and a human-sized humanoid robot HRP-4. The left three images showcase the interaction with robot's determined sequence of movements, while the right three images capture the dynamic interaction with robot's improvised movements generated by real-time gesture responsive framework.

movements into corresponding robotic movements. The data is transmitted directly from tracking sensors to the robot control interface and retargeted (with dynamic filtering) onto the robot body, as shown in Fig. 6.

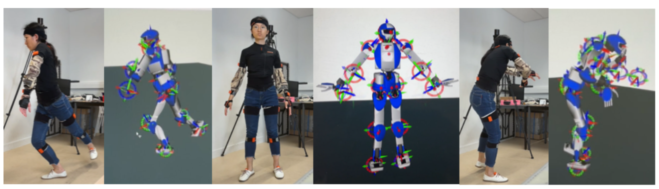

Fig. 6. The dancer discoverd different movements and transmitted them to the robot to complete the determined sequence of movements, K_j, executed by the robot during the non-responsive part of the performance.

D. Dancer, robotic performance and co-creation

The proposed real-time gesture responsive framework serves as a key role in exploring the dynamics of human-robot interaction and their co-creation within live dance performances, results are depicted in Fig. 5.

Grounded in choreographic principles, this framework's gesture classification system defines artistic expression gestures, providing a structured yet versatile framework for interpreting the dancer's movements. This allows for dancer to create diverse range of dance expression while maintaining cohesion within predetermined gesture classes. Additionally, the integration of a policy function within the robot's responsive movements control enable robot's active participation in the performance narrative, allowing the robot to dynamically select optimal actions in response to the dancer's gestures. By considering the time sequence information of the dancer's movements, the robot's responses become unpredictable, enriching the interaction with spontaneity and fluidity.

This dynamic exchange and interaction between the dancer and the robot allow us to reimagine the expressive potential of both human and humanoid bodies. Characterized by improvisational elements, where the robot's movements prompt adaptive responses from the dancer in real-time, this improvisational process, driven by intuitive expression, fosters the exploration of various forms of movement. Moreover, the interviews with the audience during our post-performance analysis, reveals a rethinking of the performance concept in observational experience. Audience members emphasize a shared experience of profound, reverent silence that transcends the boundaries of the auditorium, along with a shared synchronization of breath with the rhythmic essence during the performance. This shared experience highlighted the specific *enaction* moment, as mentioned in [32] and [21], wherein being in *(en)* action is a looping redefinition of what our body fully lives and experiences with the environment and thus, the perception is guided by action. As the audience watches the performance which is created based on pursuing the shared rhythm under the mutual adaptation and improvised co-creation, the auditorium environment is transformed, creating a new shared experience of close-to-freezing *enaction* time. This engagement ultimately transforms the audience's observational experience into a participatory one.

The entire performance can be visualized in: `www.youtube.com/watch?v=iAVdj0rey5M`

V. Conclusion

In this research, at the boundary of arts, robotics, and human-robot interactive communication, we delve into the intersection between interaction technologies, performance concepts, and the expressive potential of human and humanoid robot bodies within an experimental stage space. The presented approach introduces a lightweight, real-time gesture responsive framework that merges principles from improvised choreography and robotics, facilitating the integration of human-sized humanoid robots into artistic dance live performances. Through collaborative improvisations, the dancer and the human-sized humanoid robot synergistically combine their abilities to create movements and convey emotions, transcending traditional boundaries of human-robot interaction. This process not only reshapes the observational experience of the audience but also foster the emergence of a cognitive domain where understanding and emotion intertwine.

We designed this lightweight framework structure to first explore the artistic intention of improvisation and co-creation between dancer and human-sized humanoid robot in real-time. However, integrating advanced framework like transformer-based model while generating artistic meaningful movements is also feasible in the future work, as well as considering human-to-humanoid whole body control into performance stage settings, could open up larger possibilities for the integration of human-sized humanoid robots in dance performances for artists.

APPENDIX

We provided our fictional narrative script of improvised human-robot dance performance bellow:

In the unfolding narrative, the protagonist assumes the role of an isolated inhabitant confined within the confines of her apartment, grappling with a cacophony of emotions ranging from fear, hate, and joy to bouts of inexplicable ecstasy and despondency, triggered by the looming threat of external organic entities. Amidst her emotional turmoil, a temporal solace emerges in the form of the humanoid robot, mirroring her physical dimensions and serving as a source of companionship. A delicate interplay unfolds as she shares intimate moments with the robot, teaching it different movements and engaging in heartfelt conversations during the prolonged period of social seclusion. The interaction, at times, reveals the robot's mechanical and detached responses, while occasionally exuding an autonomous warmth, punctuated by unexpected surprises. Despite the initial challenges in communication, the robot gradually comprehends her intentions, drawing from its memory bank intertwined with her own experiences. This convergence of memories forms a poignant link, fostering a semblance of comfort, and catalyzing the evolution of her vulnerabilities in this temporal voyage. Moreover, the lurking presence of the external organic entities evolves through time, and the fear and joy turn to trigger her to construct a new relationship with the robot.

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