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Xinzhong Lu
University of Dayton

Ju Shen
University of Dayton, jshen1@udayton.edu

Saverio Perugini
University of Dayton, sperugini1@udayton.edu

Jianjun Yang
University of North Georgia

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An Immersive Telepresence System using RGB-D Sensors and Head Mounted Display

Xinzhong Lu*, Ju Shen*, Saverio Perugini*, Jianjun Yang†

*Department of Computer Science, University of Dayton

†Department of Computer Science, University of North Georgia

Abstract—We present a tele-immersive system that enables people to interact with each other in a virtual world using body gestures in addition to verbal communication. Beyond the obvious applications, including general online conversations and gaming, we hypothesize that our proposed system would be particularly beneficial to education by offering rich visual contents and interactivity. One distinct feature is the integration of egocentric pose recognition that allows participants to use their gestures to demonstrate and manipulate virtual objects simultaneously. This functionality enables the instructor to effectively and efficiently explain and illustrate complex concepts or sophisticated problems in an intuitive manner. The highly interactive and flexible environment can capture and sustain more student attention than the traditional classroom setting and, thus, delivers a compelling experience to the students. Our main focus here is to investigate possible solutions for the system design and implementation and devise strategies for fast, efficient computation suitable for visual data processing and network transmission. We describe the technique and experiments in details and provide quantitative performance results, demonstrating our system can be run comfortably and reliably for different application scenarios. Our preliminary results are promising and demonstrate the potential for more compelling directions in cyberlearning.

Keywords-Tele-immersive systems, video conferencing, RGB-D systems, virtual reality, virtual environments, interactive media, head mounted display (HMD)

I. INTRODUCTION

With the advent of internet and multimedia technology, online video chatting (e.g., Skype) has become a popular communication tool in daily life. The face-to-face visual effects and synchronized voices allow people to talk remotely with convenience. The advantages of reduced time and financial cost, and higher flexibility, make it widely used in many tasks, such as business conferences and job interviews. However, despite the benefits for general communication purposes, online video chatting has inherent difficulties to be adapted for more specific uses. For example, in the process of training, or classroom teaching, more interactivity is necessary. For example, the teacher may use an object or a tool to demonstrate and explain some sophisticated concepts. Body movement or gesture sometimes can offer important cues to improve and enhance the absorption, understanding, and retention of the material. For such scenarios, the traditional online video chatting may fail to perform desirably. The typical fixed webcam setting with static perspective,

narrow field of view, and limited interactivity has limited capabilities. To mitigate the limitations, virtual reality (VR) can be an appropriate compensation that utilizes advanced vision, graphics techniques, and novel hardware to create a more friendly and immersive experience.

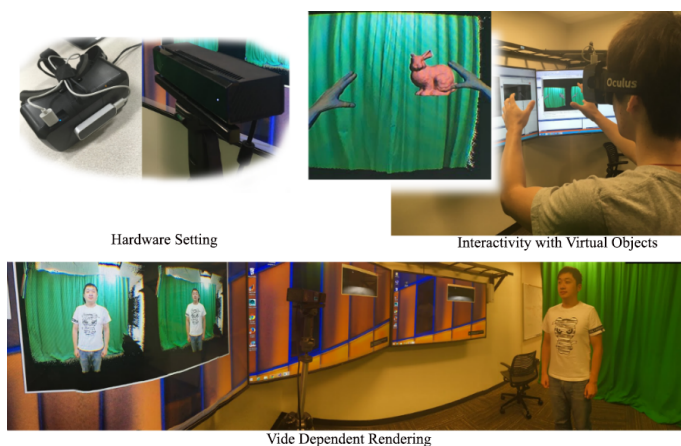


Figure 1. The overview of our proposed Tele-immersive system.

Recently, tele-immersive (TI)-based systems are gaining popularity in both research and practice, aiming to provide a natural and immersive user experience with more intuitive interactions and better visual quality. Some commercial conferencing systems, such as Cisco Telepresence and Hewlett-Packard Halo systems, demonstrate exciting features, including life-size video view, stereo audio, and high visual effects of rendering. Compared to the traditional webcam-based video chatting, these systems represent a substantial improvement.

Despite these improvements, these systems still fall short of offering realistic immersive experiences. One common and critical defect is the lack of the view dependent rendering. The observed visual contents from the screen are relatively static against the user's view point, which is not consistent with real world perception. This absence of this feature fails to effectively preserve mutual eye gaze and potentially distracts users' attention. Another drawback of existing systems is the exclusive use of conventional interaction, which only concentrates on oral communication and ignores non-verbal cues such as body gestures. For many

online interactions, or collaborations, non-verbal communication has the potential expressivity to vividly convey useful information. Thus, a desirable tele-immersive system should satisfy the following properties:

- **Correct co-location geometry between users:** during telecommunication, users are projected into a particular virtual environment. To offer the sense of face-to-face communication, we need to accurately place each user in the right coordinate space to provide the expected virtual perception.
- **Dynamic view dependent rendering:** to generate realistic visual effects and enhance eye gaze, we need to render the screen based on the user's viewpoint position in the virtual space. As the viewpoint moves, the observed objects should change accordingly so that they conform to the perception principle in physical world.
- **Rich non-verbal interaction:** by applying VR technology, the platform is empowered with the capability of capturing non-verbal cues to enrich the interactivity. Information such as body gesture, physical distance, and size, should be incorporated with audiovisual media for better accuracy, higher flexibility, and efficiency.
- **Realtime performance:** as an essential prerequisite, the system should run at interactive speed to offer liberal communication in unobstructed space. For a typical TI system, most of the computational load concentrates on two components: visual content generation and network transmission. It is crucial to make the system computationally tractable for automatic recognition, fast rendering, and large visual data transportation through optimized strategies.

Motivated by these requirements, we present a highly interactive, tele-immersive system for effective remote communication. We anticipate the proposed technique will offer a flexible platform for a wide range of applications, especially for educational purposes and applications. The system setup is shown in Fig. 1. We use head mounted display (HMD) as the communication media instead of traditional desktop-size displays; a pair of low-cost *Kinect* (RGB-D) cameras and standard microphones used to capture user's input; an infrared light sensor is utilized for gesture capture and recognition from egocentric perspective (i.e., first-person view).

Our goal is to enable users from remote places to communicate and collaborate in a realistic face-to-face manner. Two distinct features of our system are: i) realtime view-dependent rendering is offered so that the displayed content updates dynamically according to the view position and orientation, and ii) users are allowed to directly operate on virtual objects in an intuitive manner. As the example in Fig. 1 illustrates, the teacher uses the bunny object to explain a particular concept. He can hold, rotate, and

manipulate it with her hands. Moreover, multi-users can work collaboratively manipulate the shared virtual objects in a synchronized manner. Each user can not only see each other, but also observe the consequences of each other's actions reflected on the virtual objects. For instance, if both users push a virtual ball from different directions, they will perceive the transformation (i.e., shape or position changes) of the ball caused by their actions.

However, achieving these desired functionalities is challenging. First, to accurately generate realistic perspective views, we need to acquire correct 3D scene geometry and user's viewpoint positions. Second, user's body poses need to be detected and tracked in realtime. Third, to effectively produce user's interactions among each other and with the surrounding virtual environment, the system should be able to handle coordinate synchronization, collision detection by incorporating physical properties, such as object contours, and weight. Thus, our primary efforts are directed toward designing, implementing, and optimizing the system by identifying each module individually and collectively integrating them.

II. SYSTEM ARCHITECTURE

The overview of our proposed TI system is depicted in Fig. 1 with the hardware setup and user demonstration. At each user's end of the proposed client-to-client scenario, an RGB-D-based system, a head mounted display (*Oculus Rift*), and motion detection sensor operate together for input capture and data processing. For the RGB-D acquisition, we choose the *Kinect* camera as it is widely accessible and low-cost. For the motion detection, the *LeapMotion* device is used, which is a portable device consisting of two cameras and three infrared LEDs. Since the novelty of our system is designed primarily for producing rich visual effects, we only focus on the video-sensing devices in our prototype. Additional devices, such as an audio recorder and remote controller, can be incorporated for a specific application, as necessary. As mention above, the system is designed to offer two types of interactivity for educational scenarios.

A. Functionalities

For eye-gazing interactivity, the instructor delivers a presentation or lecture by facing the *Kinect* without wearing HDM, as shown in Fig. 2. This is a common scenario for online course instruction, where eye contact can be established between the instructor and student. Fig. 2 illustrates student perception from the HMD remotely. The instructor's image is rendered on the display based on the user's view perspective. Since the imaging process strictly follows the camera projection principle from 3D-to-2D, it delivers realistic views, which are faithful to the physical size of the captured object. Hence, observers can have a sensation of experiencing a face-to-face lecture. Furthermore, the lecture

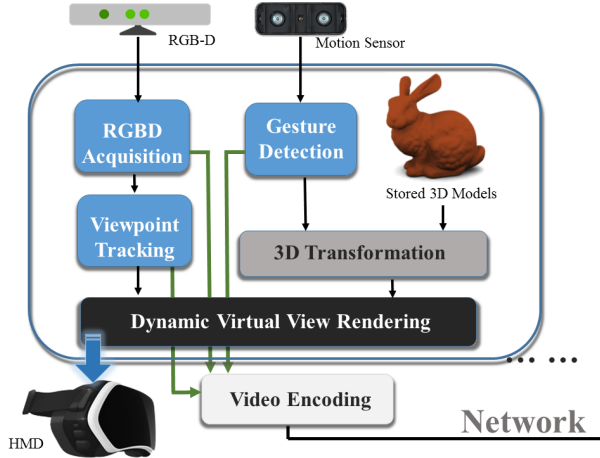


Figure 2. System architecture and pipeline.

can also be perceived from different viewpoints according to the observer’s preference, as shown in Fig. 2.

To enhance mutual understanding and facilitate teaching activities, our second distinct functional module offers richer non-verbal interaction between users. By empowering the instructor to demonstrate and manipulate objects in virtual space, the capabilities of the system enable the instructor to capture and sustain more student attention through concrete examples. Concomitantly, in response students can perform similar operations on the targeted objects in an interactive manner. The system is responsible for incorporating the input from each perspective (student and instructor) and synchronize the shared view on the virtual object accordingly. We hypothesize that such interactivity is especially useful to explain complex concepts. For example, in an engineering mechanics course, it is often challenging to verbally or textually describe a sophisticated system. Students need to visually see the structure and work flow to gain deep, profound understanding of the system.

B. The Pipeline

Fig. 2 describes the system’s pipeline, which is comprised of six different functional components. According to their responsibilities, these components can be further categorized into four groups, as indicated by different colors: blue for vision task; dark gray for graphics task; black for virtual view rendering; and light gray for video compression for transmission. These components are distributed on each user’s end and provide remote communication across network.

Vision Task: as the input stage processing, where color and depth data are captured from the *Kinect* device; meanwhile, the *LeapMotion* controllers obtain a grayscale stereo image of the near-infrared light spectrum, separated into the left and right cameras. These two input streams feed into the RGB-D acquisition, viewpoint tracking, and gesture detection

components, respectively. These components produce three outcomes: the reconstructed 3D of the captured scene with textures and user’s viewpoint position, and user’s corresponding pose estimation.

Graphics Task: In addition to the sensor’s input, our system uses pre-stored 3D models to synthesize virtual scenes, which is the main responsibility of the 3D transformation component. For each user, the same copy of models is stored and loaded locally to avoid heavy data transmission. During running time, only the updated information are synchronized across the network, such as object position and orientation changes. This component also offers collision detection, which is essential for realistic rendering and correct user interactions.

Virtual View Rendering: the reason this component is separated from the graphics tasks is due to its mixture of input from multiple resources. One input is the detected local user’s viewpoint position, which plays a role as the center of a virtual camera that projects 3D data onto the 2D image plane for dynamic perspective rendering. Another input is the pre-stored virtual objects, including user’s virtual body. In addition to the local input, remote data also contribute to the final view synthesis. For instance, the captured (color and depth) images of other users are transmitted through the network and merge with local virtual objects.

Video Compression: to ensure realtime performance, we also need to consider the data exchange of large visual contents across the network. Some video compression or tracking strategies can be developed to boost the transmission speed.

III. KEY COMPONENT TECHNOLOGIES

A. Accurate 3D acquisition

The 3D point cloud and its color texture information are obtained by the *Kinect* camera. As the captured depth image has the depth value available for each pixel. Based on the intrinsic parameters of the camera and the measured depth, we can obtain the corresponding 3D point by applying an inverse camera projection operation. Thus, for each pixel on the color image, we can compute the tuple $\{X, Y, Z, R, G, B\}$ where R, G, B are the three color channels.

In order to project users into an immersive virtual environment, first we need to extract their texture and geometry from the acquired 3D point cloud. Depth value for each pixel provides a useful clue allowing us to easily separate the foreground and background. However, Noise present in the depth image that can significantly impair the quality of the separation. To handle this problem, we use our proposed two-layer pixel labeling strategy via a probabilistic framework that incorporates background and measurement modeling as well as available observations in the missing depth neighborhood [2]. The labeling procedure is formatted

as a *Maximum a Posteriori* (MAP) problem:

$$X_G^{map} \triangleq \arg \max_{x_G} \left(\sum_{s,t} \log \psi(x_s, x_t) + \sum_s \log \phi(x_s) \right)$$

where, s and t defines the neighbor pixel indices around the target pixel. The spatial term $\psi(x_s, x_t)$ and prior term $\phi(x_s)$ are derived from the depth continuity and color similarities. To solve this *Markov Random Filed (MRF)* configuration, an optimal solution can be approximated by using *Loopy Belief Propagation (LBP)* [4].

B. View Rendering

For dynamic virtual view rendering, a key task is to accurately track the viewpoint in realtime. To aid this procedure, we can possibly rely on three resources: color image, depth image, and the Oculus positioning tracker. As each of them has its own limitations, it would be beneficial if we can let the three trackers work corporately in a boosting manner.

For the depth based tracking, our earlier work can be adopted by approximating the head as a sphere and treating the center as our target viewpoint [3]. A complete head silhouette is obtained by inferring a curvature curve through holes filling and outline smoothing via the *Morphological opening and closing* technique. However, the depth sensor fails to accurately detect the target when it is out of the range [80cm, 400cm]. As a compensation, the Oculus positioning tracker and color image can provide additional cues. An easy and naive way is to use thresholding to switch the responsibilities between these three resources. Depth tracking is performed when the target drops into a valid range. Otherwise, we can applied color tracking algorithm, such as Camshift [6], or Oculus positioning. The estimated center of the circle on the camera plane is temporally smoothed with a Kalman filter. This simple but straightforward method works well for us. However, more advanced approaches can be employed for better robustness and generality. For example, the particle filter for RGB-D scene can be applied to solve the 6-DOF pose tracking problem [5], where the posterior probability density function $p(\mathbf{X}_t | \mathbf{Z}_{1:t})$ for estimating object trajectory at time t is represented as a set of weighted particles: $\mathcal{S}_t = \{(\mathbf{X}_t^{(1)}, \pi_t^{(1)}), \dots, (\mathbf{X}_t^{(N)}, \pi_t^{(N)})\}$.

C. Interactivity

The core of interactivity between users in virtual environment is the collision detection, which imposes constraints to the object's motion by collisions with other objects. The *LeapMotion* device offers an efficient hands and arms detection in realtime. As the estimated gesture is from egocentric perspective (first-person view), we need first to convert the 3D positions from each user's end to the global coordinate by using the extrinsics. For each user i , according to its predefined position \mathbf{t} and orientation \mathbf{R} in the virtual space, an detected 3D point \mathbf{p} from the user's perspective can be transformed to the global

coordinate as: $\mathbf{p}' = [\mathbf{R}^{(i)}, -\mathbf{R}^{(i)}\mathbf{t}^{(i)}; \mathbf{0}, 1] \cdot \mathbf{p}$. After the coordinate synchronization, we need to identify any axis-alignment or overlapping between all the user's 3D points \mathbf{p}' and the virtual environments. An intuitive solution is to use bounding boxes through dimension reduction, such as *Binary Space Partition (BSP)* method [7]. For our prototype implementation, we wrap up each object by the axis-aligned bounding boxes as bounding volumes [8]. It assumes if two bodies collide in three dimensional space, their orthogonal projection onto the xy , yz , and xz -planes and x , y , and z -axes must overlap. The *Sweep and Prune* algorithm is adopted to reduce the number of pairwise collision tests by eliminating polytope pairs [8]. To accommodate more complex models in large environments, parallelization based strategies can be employed for further optimization, such as the *Potentially Colliding Set (PCS)* approach, which can be conveniently adapted for GPU processing [9].

D. Network Transmission

For realtime performance, we adopt a Server-Client distributed architecture to deal with remote environment and high computation complexity. As depicted in Fig. 2, each client is responsible for an RGB-D camera, a motion sensor, and local 3D models. To unburden the transmission load, the tasks of 3D point cloud processing, viewpoint estimate, collision detection, and rendering are all carried out at the client level. Each client sends out a pair of RGB and depth images, detected view point (a 3D point vector), body tracking estimation (multiple 3D points for the detected body joints), and collision detection results to the server. The server then combines all the received images, refine the estimations and then distribute the data back to the clients. As most of the heavy transmission load concentrates on the RGB-D image pairs, we applied our proposed *CamShift* based algorithm to transmit a compressed version of images on the network [10].

IV. THE PERFORMANCE

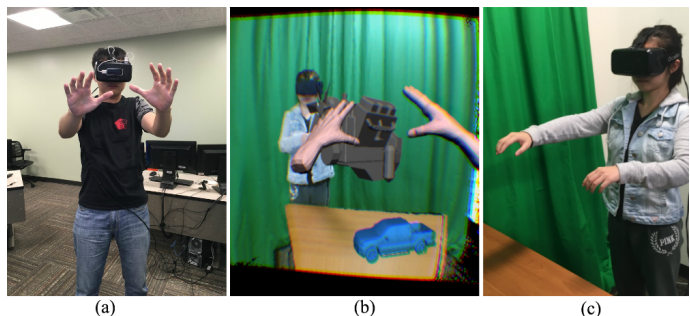


Figure 3. Interaction between users

A. Quality Demonstration

Scenario 1: For this scenario, it shows how users coordinate and share resources with others. Fig. 3 (a), (c) demonstrate a scenario that two people are collaborating remotely. Fig. 3 (b) shows what the user (a) can observe from the HMD: user’s hands (presented by the virtual 3D model), shared virtual objects, and the collaborator’s image captured remotely. In the example, it shows the girl is raising up a 3D model for her collaborator to catch. This process is synchronized and delivered to the HMD of both users, which allow them to sense such interactivity virtually.

Scenario 2: Apart from the interactivity, the advantages for lecturing can also be identified, such as online tutoring applications. Fig. 4(a) demonstrates how a learner can perceive the lecturer from the HMD. A true face-to-face sensation is created by offering life-size views and flexible distance adjustment. According to the lecture topic, different immersive virtual environments can be rendered, which can help the lecturer give more vivid and clear explanation.

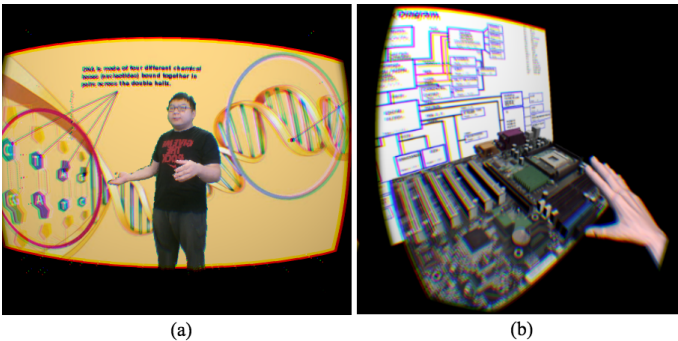


Figure 4. Face-to-face lecture and online practice

Scenario 3: For traditional online lectures, it often suffers from a one-way mode that students act as a passive observer. As an alternative, our system allows students to practice during learning. Fig. 4(b) shows student exercises in a motherboard assembling course. The student can virtually practice hardware installation while reading instructions.

B. Quantity Evaluation

Accuracy: To verify the interactivity accuracy, we compare the estimated body gestures in the virtual space with the ground truth, which is based on the physical measurement of the distances between the HMD and the checkerboard (See Fig 5(a)). We let users place their hands at different positions against the checkerboard with their x, y, z coordinates within the ranges: $x \in [-30cm, 30cm]$, $y \in [-20cm, 20cm]$, and $z \in [5cm, 40cm]$. Fig 5(b) shows the contrast between the gesture estimation in the virtual world and physical measurement in the real world along the x, y, z -axes. The standard deviation of their offset is managed to be less than $1.2cm$ among all the directions.

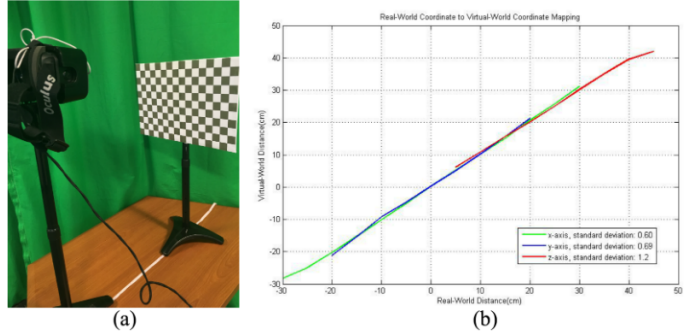


Figure 5. Accuracy measurement between the virtual and physical worlds

Time performance: the preliminary prototype is implemented using C++, OpenCV, and OpenGL library, running at each client machine with Intel Core i7-4790 (8M Cache, 4.0), 16GB Dual Channel DDR3 1600MHz RAM. The computational performance for each component is shown as the table below, which is measured based on per frame processing speed. We tested different 3D model meshes with the average time cost around $25ms$ for processing $3.3M$ polygons. Without any parallelization, our method can process 424×512 video at $14fps$, which is close to an interactive speed.

	Processing Time	rendering Time
3D Object	25 ms	9 ms
RGB-D processing	23 ms	< 1 ms
Collision Detection	< 1 ms	< 1 ms
Network Transmission	5 ms	–
Total Time	≈ 73ms (framerate ≈ 14fps)	

V. APPLICATION IN EDUCATION

Immersive learning experiences such as those which our system helps support have the potential to alter the way educators think about and deliver primary and higher education, and the methods by which students engaging in experiential learning [11].

Virtual environments such the system we describe, which support the synchronous physical manipulation of objects by participants in a collaborative, mixed-initiative motif [13], both blur the boundaries between teacher and student, and foster enhanced student-student collaboration. While the educational applications of such collaborative, simultaneous object manipulation are diverse and countless from teaching children to write to advanced military training exercises, we focus on two broad and progressive application categories within education here and make some cursory remarks.

- *Developing motor skills in kindergarten children:* An important, early educational application of our system is the development of motor skills among pre-adolescent children, where mutual manipulation of objects is an integral part of the learning process. Such

an application can evolve into, for example, teaching young children penmanship in kindergarten (i.e., a teacher can help the pupil hold a pencil in her hand and demonstrate proper technique) or support for robotic-oriented ways to teach computer programming to children as made possible through the *KIBO* robot kit¹.

- *STEM applications across a range of high school subjects, especially using virtual modeling and simulation technologies*: our work also can support teachers and students helping each other explore and manipulate objects in the study of physical, astronomical, biological, chemical, and computational phenomena. These objects can exist in real-world, physical models or virtual simulations. For instance, students can collaboratively and simultaneously manipulate 3D object models of molecular structures, chemical bonds, solar systems, or even multi-dimensional hypothesis spaces in the study of machine learning.

A recent article in the Huffington Post showcases seven cyberlearning technologies including ‘tools for real-time collaboration,’ an area in which our work lies, funded by NSF that are transforming education [11]. Our work is focused on collaborative manipulation of objects in virtual environments and, thus, can complement and support many of these efforts, especially in the two areas of education briefly mentioned above. Chris Hoadley, the program officer at NSF who leads the Cyberlearning program, has said: “I believe it’s only by advancing technology design and learning research together that we’ll be able to imagine the future of learning” [11].

VI. CONCLUSION

In this paper, we have presented the design and realization of an immersive telepresence system by employing RGB-D systems, motion sensors, head mounted displays, and networking setup. We demonstrated the implementation and optimization strategies of each component and integrate them systematically. The system can be run in realtime, which is indeed a proof of feasibility for practical applications. We addressed its potential benefits in future education, particularly in cyberlearning. As such, one of our future plans is to conduct an extensive evaluation of user experience on using the proposed system for learning different tasks. From the technical perspective, to further improve the current prototype, related key technology will be explored to deal with more complex environment and a larger number of users.

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¹<http://tkroboticsnetwork.ning.com/kibo>