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Visible Light Positioning for Location-Based Services in Industry 4.0

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Abstract: Industry 4.0 refers to the evolution in manufacturing from computerization to fully cyberphysical systems that exploit rich sensor data, adaptive real-time safety-critical control, and machine learning. An important aspect of this vision is the sensing and subsequent association of objects in the physical world with their cyber and virtual counterparts. In this paper we propose Visible Light Positioning (VLP) as an enabler for these Industry 4.0 applications. We also explore sensing techniques, including cameras (and depth sensors), and other light-based solutions for object positioning and detection along with their respective limitations. We then demonstrate an application of positioning for real time robot control in an interactive multiparty cyber-physical-virtual deployment. Lastly, based on our experience with this cyber-physical-virtual application, we propose Ray-Surface Positioning (RSP), a novel VLP technique, as a low cost positioning system for Industry 4.0.

Keywords: Visible Light Positioning, Light-based Positioning, Optical Wireless Communications, Steering, Location-based Services, Industry 4.0.

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1 Introduction

The Fourth Industrial Revolution (Industry 4.0 – I4.0) is the domain of cyberphysical systems embracing contemporary computing and communications as applied to design, manufacturing, logistics, and related applications [1–4]. Our interpretation of this vision is that current technologic trends can be harnessed to gain significant scale and efficiency improvements by adopting concepts embodied in robotics, artificial intelligence, machine-machine communications, cloud computing, and autonomous and decentralized control. While we support the grandiosity of this vision, we also recognize that the many embodied concepts must be successfully integrated in the context of a manufacturing problem and thus must be modular and robust, exposing appropriate interfaces, and providing data to multiple contributing components. To this end, we concentrate on a single modular component as an enabler to I4.0: indoor positioning technology.

We use the term "location-based service" (LBS) aptly as location or position information is a requirement for many aspects of cyberphysical and virtual systems and should be exposed and utilized differently among the distinct components of an I4.0 application. In this paper we focus on the use of physical data (e.g., position) to support the cyberphysical system, typically, but not exclusively, for automation and robotics and also to support virtual spaces, in interfacing humans and machines through visualization. We call this a "cyber-physical-virtual" association.

For I4.0, target devices that require the use of physical or virtual position include: augmented reality/virtual reality (AR/VR) headsets, robots, machines, mobile devices, and other smart devices. With indoor positioning, reliable and secure cyberphysical services (internet-of-things – IoT), point-to-point optical wireless communications (free-space optics, visible light communication – FSO, VLC) and virtual content (AR/VR) can be delivered to specific localized devices, e.g., machines that autonomously, intelligently, and securely move and accomplish tasks on their own with AR guiding human interactions. In such instances, there can be thousands of devices to maintain and track and infrastructure-based solutions are logically more feasible than device-centric solutions. In fact, this infrastructure-based paradigm has worked successfully outdoors in Global Navigation Satellite Systems (GNSS), which is a single instantiation of a satellite network servicing any number of GNSS enabled devices.

Visible Light Positioning (VLP) has emerged from VLC as a competitive infrastructure-based indoor positioning system that yields 2D or 3D position information to participating devices [5]. VLP is better positioned in comparison to other infrastructure solutions due to the ubiquity of lighting in work environments and the potential to share the infrastructure cost with indoor lighting and communications. Current VLP solutions also offer centimeter-level accuracy and, as an active photodiode (PD) positioning solution, privacy-preservation – users can opt in or out of the positioning service [6]. Fig. 1 shows the overhead VLP paradigm, highlighting AR/VR headsets and automation as two key I4.0 applications. Although there are many variants of VLP that utilize different modalities and different mathematical models to varying results, this paper focuses on the needs of I4.0, which involves high accuracy positioning at large scale and low cost.

The remainder of the paper is organized as follows: Section 2 reviews the requirements of I4.0 and describes the limits of existing positioning systems in the context of these requirements; Section 3 describes and demonstrates a LBS as a game implementation with similar characteristics as an I4.0 application; Section 4 proposes specific improvements to VLP to satisfy gaps in the existing state-of-the-art, namely how our VLP methodology targets these gaps; and Section 5 concludes the paper.

2 Requirements of Industry 4.0

The exact definition and requirements of I4.0 are inherently in flux, but there are broad characterizations of what constitutes the new paradigm. Elements include autonomous and decentralized control, real-time monitoring, communications, and self-optimization [1–4]. Tools necessary to bring this vision to bear are broad and encompass machine learning, machine-machine communications, and many other techniques. We focus on two aspects: (1) realizing real-time positioning and (2) association of positioning data with virtual models for enhancing human interaction. The required positioning technology to identify where objects are located manifests either as peripherals co-located with the target object (like sensors on autonomous robots or vehicles) or as a service provided by an infrastructure (e.g., GPS or VLP).

2.1 Overview of Industry 4.0 Characteristics and Positioning

Positioning can be applied at different scales. With respect to indoor positioning, applications in I4.0 span from presence detection down to sub-cm accuracy. These applications are briefly summarized:

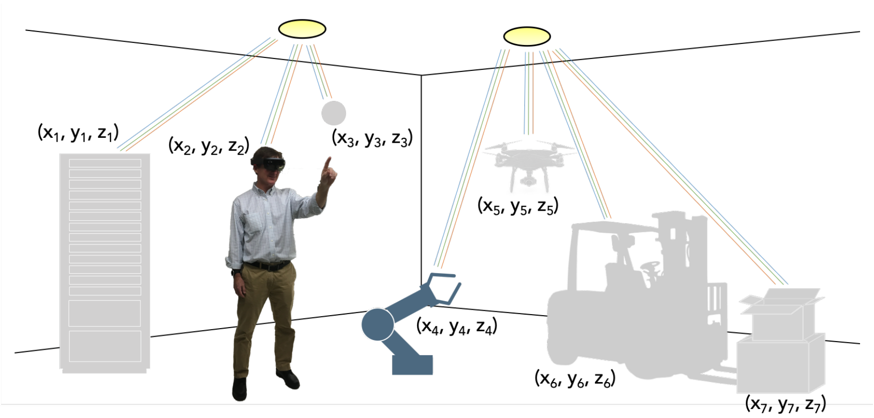

Figure 1: Location-based services using VLP: augmented reality (AR) and robot positioning

- Presence: Is an object in the building? This might be determined by coarse means such as a door card reader, a WiFi/BLE beaconing technique, or a smart label.
- Navigation: Autonomous transitions between two waypoints guided by beacons, ranging, and positioning.
- Collision avoidance: Provided by high-fidelity ranging sensors such as ultrasound, IR, or LIDAR.
- Proximity: For when a human enters a danger area. Detection provided by ranging or imaging. Also, for secure interactions with near-field communications (NFC).
- Control: Tool placement on a workpiece with high accuracy: provided by imaging, ranging, IMUs, and positioning. Tools can be virtual (in AR) or physical.

Positioning of course extends into additional derivatives (velocity and acceleration) but are not considered in this paper. There is also the idea to remove wired communications in favor of wireless communications to reduce maintenance of high stress wired components, e.g., in a robotic arm, and to allow for reconfigurability [7]. This is an area where position information can aid the communication system, particularly if the wireless link is a high-speed, line-of-sight FSO link.

2.2 Supporting Industry 4.0 AR with VLP

While knowing the location of machines and devices will aid in automation and cyberphysical services (e.g., data logging), position information will also aid in augmenting the virtual world onto the physical world. The unmet technical needs in I4.0 AR applications relate to high accuracy (cm-scale) positioning at low cost, fast target acquisition, freedom from wires, high-speed communications, and tracking of large number of targets, especially when both the target and headset are in motion. A key concept here is the use of the positioning system to associate physical objects with virtual objects rendered to the AR device. This is where a high-accuracy light-based indoor positioning technique can address the performance needs of next generation I4.0 AR.

2.2.1 Physical to Virtual Association

Fig. 2 illustrates the physical to virtual world association of how a target object (the physical circuit board) is identified and how the identified object is associated with a virtual object that is overlaid onto the AR screen relative to the positions and orientations of the AR user and the physical object. There are many exciting use cases related to how people interact with physical objects similar in type to Fig. 2. In such cases, virtual content provided by the AR headset is associated with objects or devices in the physical world that are positioned using an overhead positioning infrastructure – overhead because it is both more accessible to multiple targets and is more likely to provide continuous coverage.

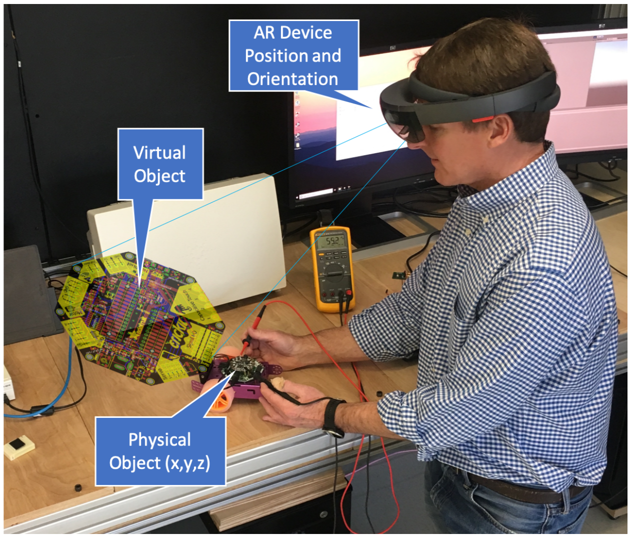

Figure 2: Physical to virtual association with positioning information

2.2.2 Existing Techniques

Existing technologies for supporting this emerging AR vision are limited. These limits relate to how an AR headset is located, tracked, and provided with real time data streams. For example, smartphone-based solutions rely on image analysis to identify a target object or target label. Devices such as the Microsoft HoloLens (which we have evaluated) use imaging but with additional sensors for depth perception. These association methods, including the methods with depth sensors, severely limit the ability to reconcile the speed and motion of the headset or target; the resulting experience is haphazard. Successful AR demonstrations on these devices require holding a steady gaze on a target to facilitate, maintain, and update physical-to-virtual association. The amount of light in the room also affects performance. In addition, there is a high processing (and power) cost on each unit. Offloading processing to the cloud would require a high "bandwidth" link to the AR device as high-speed and low-latency are critical to rendering virtual scenes that accompany real-world physics of the targets. This is a motivation for high-speed FSO in I4.0, which itself would benefit from positioning information. Targeting multiple objects is also very limited with self-contained sensing cameras. On the other hand, always-available infrastructure-based positioning enables many target devices to be localized before the targets enter the field-of-view (FOV) of the AR headset, which in turn allows preemptive generation of virtual content.

With respect to infrastructure-based systems, competing commercially available technology for low-cost indoor positioning includes products such as RF (WiFi, BLE, etc.) beacons, lighting (e.g., Bytelight, OLEDComm), ultra-wide band, ultrasound (e.g., Cricket), and others [8]. These solutions use a myriad of techniques including fingerprinting, received-signal-strength (RSS), multilateration, and time-of-flight (TOF) but have limited positioning accuracy with best case accuracy in the 10s of cm [8]. Newer VLP systems with varying receiver complexities and relying on angle-of-arrival (AOA) and mixed mediums (e.g., RF and light) provide 3D positioning in the centimeters or finer [6, 9]. There are also purely laser-based solutions including spinning lasers [10]. For sub-millimeter positioning, motion capture (MoCap) systems (e.g., Optitrack) compete but at much higher system cost.

2.2.3 High Accuracy and Low Cost as a Differentiator

High accuracy is a discriminator but particularly so when realized at low cost. In telemedicine, real-time AR guidance use MoCap for tool (needle) positioning [11]. But these MoCap systems cost in the range of $10k-20k. Of course, for cutting edge surgery applications, the cost of a MoCap system is a low barrier. But for I4.0, the cost can be a nonstarter for high-accuracy positioning. By offering a lower cost alternate to motion capture, VLP opens up new applications for tracked/AR/IoT systems that link physical objects with virtual ones displayed on the AR device. Other competitors in low cost positioning include RF and light-based systems but, as mentioned previously, are limited to an accuracy in the 10s of cm and poor 3D positioning [6, 8]. This cost-accuracy barrier provides opportunity for VLP.

3 Wizard's Chess: A Demonstration Application for Industry 4.0 and VLP

To demonstrate the concepts described in the previous sections, we share experiences in developing a position-assisted AR robotic prototype modeled on "Wizard's Chess" from *Harry Potter* [12]. We refer to this prototype game as Augmented Reality/Robotic Chess (AR/RC).

The premise of AR/RC is to present an augmented experience (a graphic overlay) of a virtual experience mapped to physical objects. In this case the objects are a set of 32 identical wheeled robots, i.e., WiFi ESP32 microcontrollers with wheels and motor drivers capable of planar motion. The virtual experience consists of mapping 3D models of chess

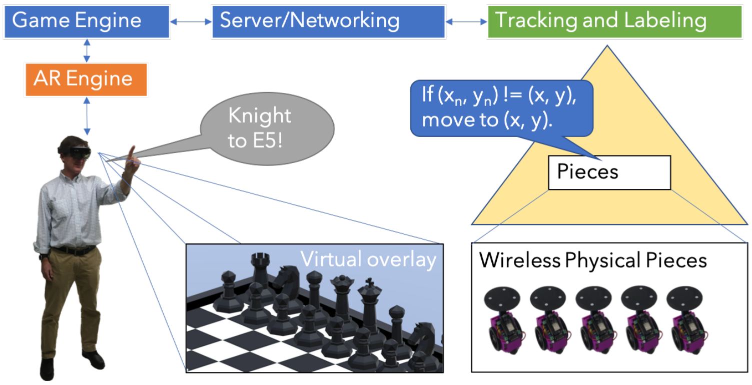

Figure 3: System overview of the Augmented Reality/Robotic Chess

pieces onto each of the 32 robots in the physical game board space. The 3D models we used were developed by Happy Pixels obtained from the Unity Asset Store. As play progresses (as moves are declared by each player), the robots autonomously locomote on the game board to assigned positions and fulfill their instructions; in some cases displacing the opponent's piece as an attack, in which case, the game engine must coordinate with the positioning system the locations of the robots so they do not bump into each other. Meanwhile the virtual overlay follows the motion of the robots and thus provides the unique virtual game experience coupled to the non-unique physical robots. This overall experience is represented in Fig. 3. Fig. 4 illustrates how the realized virtual object associated with the physical object is rendered when viewed on an AR headset. Both the AR device and the robots exploit the position information provided by the location service.

With respect to I4.0, this prototype demonstrates the linkage between tangible physical objects (robots) and a virtual coordinate system. The enabling technology here is the positioning system that is able to track the robots in real time. In this implementation, we use Optitrack, an IR MoCap system, as a stand-in for VLP, as it is a robust and ready commercial system. Future implementations will replace Optitrack for a low-cost VLP system. In the following, we describe some of the critical aspects of this positioning-enabled system that we encountered.

3.1 Establishing a common coordinate system

For an infrastructure-based positioning system, there are three different coordinate systems to manage and reconcile: (1) the physical system associated with the robots and how they navigate in the real space, (2) the virtual coordinate system associated with the AR headset and where virtual content is generated with respect to the perspective of the user, and (3) the positioning system associated with the positioning infrastructure. Initially, these three subsystems boot in their separate and individual coordinate systems. To coordinate among

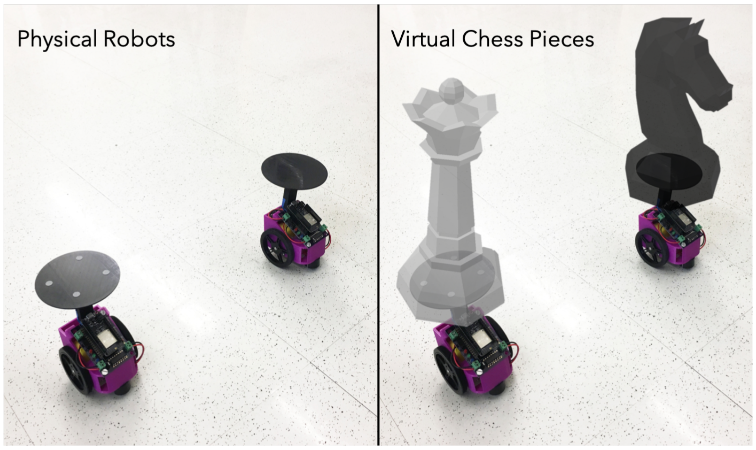

Figure 4: Virtual overlay of chess pieces onto tracked physical robots

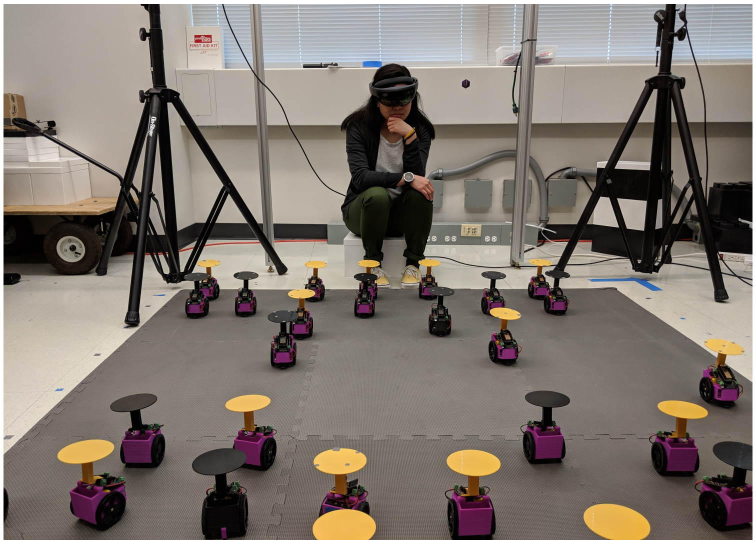

Figure 5: User wearing AR headset and 32 robotic chess pieces

these aspects requires satisfactory registration of anchor points and commissioning at start up to establish correspondences and a common coordinate system.

3.2 Multiple objects

In building out the relatively small number of robots (32 – Fig. 5 shows the scale), we encountered issues associated with growing system complexity. Problems arise in creating and attaching unique optical tags onto the robots, calibration, programming, battery charging, etc. In our design we have not reconciled how to self-provision, which is clearly a requirement for any large scale system of this type that includes provisioning of all aspects of the LBS system. One approach is to provision using active methods. An active positioning system could eliminate the look-up table associated with optical tags, image processing, prior learning, or point clouds. This is problematic for camera or time-of-flight systems. One research group addresses this issue by complementing cameras with active VLC [13]. VLP inherently as an active positioning system will not have this problem.

3.3 Real time tracking

The Optitrack system does exceptionally well at positioning in real-time. This is because Optitrack uses multiple cameras – we tested with 4 and 12 cameras – each operating at 100 fps. This rate corresponds to sampling at 10 ms intervals. This is a good latency target for most applications but is the upper bound for some virtual reality environments. Faster, less complex, and less expensive systems would enable a wider set of applications. There is also latency from the network in relying position information from the Optitrack system to the mobile robots. Active tracking at the robots will remove this latency.

3.4 Movement of both target and headset

In addition to reconciling the coordinate systems between the positioning system, real world, and augmented world, there is also a need to reconcile motion of the targets with the motion of the virtual experience, specifically an AR headset in motion. We use the Microsoft HoloLens in our system which continuously maps and processes its perception of the environment. This worked well over short intervals but tends to drift over time, creating inconstancies due to variances in sensing surroundings, people, or objects moving in and out, lighting, or non feature-rich backgrounds. Tracking and positioning of the headset by an infrastructure-based solution would mitigate this problem.

3.5 Other observations

Blockage is also a problem with a camera-based positioning system. The Optitrack camera system requires a target to be in the field-of-view of at least two cameras. Reducing the number of required cameras needed per a target would help with the blockage problem. Multilateration-based VLP systems are similarly limited [6]. Since the robots operate at floor level, we were able to adjust the camera angles to cover the playing surface. However, the 3D space is not well-covered in this configuration. Our VLP solution, described in the next section, addresses this challenge.

4 Proposed VLP for I4.0

We propose a new method for positioning and tracking objects using properties of two different intersecting light sources called Ray-Surface Positioning (RSP) [14], Fig. 6. RSP is designed to accurately position a mobile device in 3D to within a bound of less than 10 cm using an overhead reference point and to provide tracking as the device moves within an operating area. Additional light sources can be added for redundancy, scaling to larger spaces, resolving occlusions, and providing capacity to more mobile devices. With respect to I4.0 devices, e.g., AR/VR headsets, robots, machines, mobile devices, photodetectors can be easily added to these devices to accommodate the VLP system, especially given that VLC will also likely service the communicative needs of these devices. Our system is meant to replace more costly camera-based systems such as the Optitrack system described earlier and also to better handle its limitations.

4.1 Ray-Surface Positioning (RSP)

RSP is a low-cost light-based positioning system. The system employs a steerable laser (ray) in conjunction with a lighting luminaire (surface) to position devices with active receivers [14]. The ray leverages FSO communications or VLC, if using visible light, and sends its

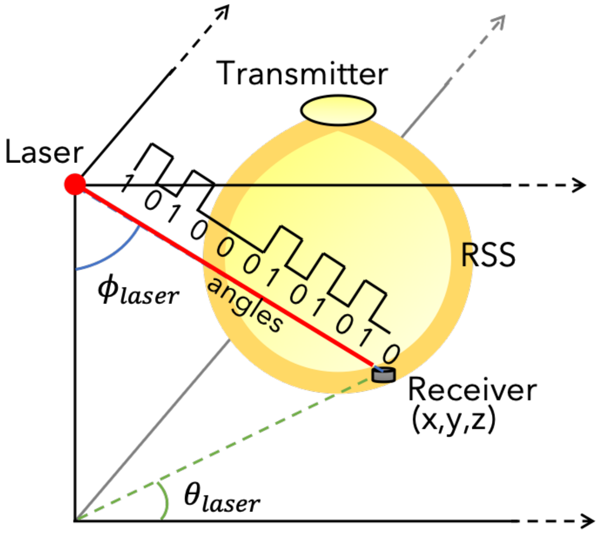

Figure 6: Ray-Surface Positioning: combination of laser source modulated with pointing angles and Lambertian source

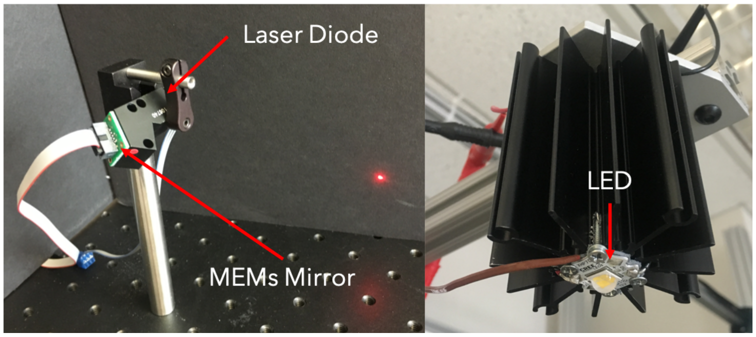

Figure 7: MEMS steering device and CREE XHP50 LED.

angle relative to itself at all times to the receiver. Modulating the laser with its pointing angle is a unique methodology to achieve angular diversity, regarding AOA at the receiver, without measuring and computing angles at the receiver. High-speed steering can be accomplished with a steerable MEMs device for pointing. Fig. 7 shows a Mirrorcle scan module (Model #EaZy 1.1) that has a 40° FOV and can steer a modulated laser beam at 1 kHz; the beam can move between any two 3D coordinates in < 1ms. The receiver, in addition to receiving the modulated pointing angles, can receive and measure optical signal strengths generated by overhead lights, a CREE XHP50 in Fig. 7. By using the characteristic Lambertian emission profile, the receiver can use RSS to determine range. From a visualization perspective, a specific RSS value creates an envelope – "balloon" – of possible position points, Fig. 6. Using the pointing angles received from the laser, a vector of potential points can be generated based on the Lambertian emission profile and thus the intersection point between the surface and ray is the estimated position [14].

RSP compares favorably in terms of accuracy versus multilateration with luminaires alone

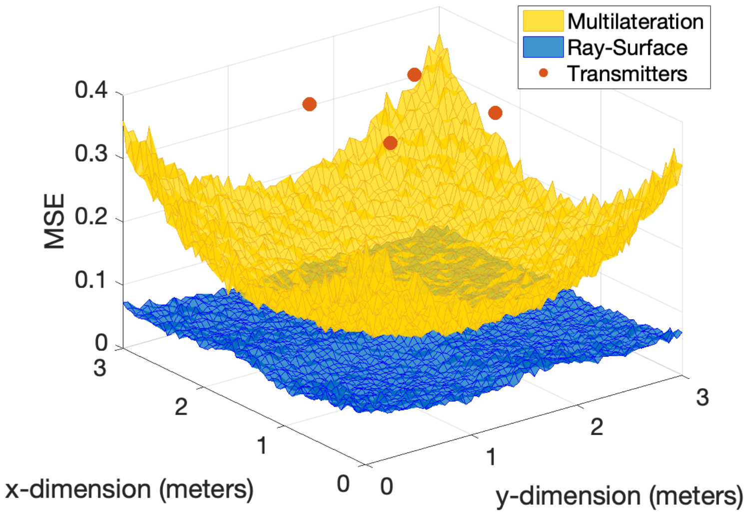

Figure 8: Ray-Surface Positioning performs better than multilateration particularly away from the center of the room

especially when considering three dimensions [14]. In fact, if the horizontal plane of object movement is known, RSP accuracy will be in the order of the size of beam width within a range of 10 m. Using the specifications for our LED and laser, Fig. 8 shows simulations of RSP performance versus multilateration in a 3 m × 3 m × 3 m room at floor level with 4 luminaires. Multilateration is the benchmark here as it is the most common VLP technique. The significant gains, particular away from the center of the room, are due to the ability of the RSP technique to choose and use the strongest signal (luminaire) available at all times if multiple luminaires are present.

4.2 RSP for Industry 4.0

As discussed earlier, LBS needs for I4.0 vary by application. VLP, and by extension, RSP, is best suited as an infrastructure-based positioning method. Advantages are the simplification of positioning using a centralized device and the ability to target multiple devices. A possible disadvantage is the use of an active receiver at the target; however, the receiver can be a very simple photodiode, and from a security standpoint, having the option to opt in or out of the positioning service is useful. The laser source can also provide ranging information for passive objects if equipped with TOF sensing.

With respect to AR and I4.0, we avoid using image processing at the receiver which greatly simplifies the size, construction, energy consumption, and cost of a headset and frees up the limited processing power to other functions. There is plenty prior work on VLP that exploit different modalities but RSP is more adept at solving the needs of AR and I4.0 than these other solutions particularly for 3D positioning as it only requires line-of-sight (LOS) to one luminaire and one laser [6]. This less strict requirement is useful given that AR headsets operate in multi-dimension where LOS to multiple luminaires is limited.

5 Conclusion

Future I4.0 applications will exploit a rich set of data originating from physical objects as provided by attached sensors and instrumented environments. These data form the basis for a variety of functions including self-organization and adaptation, decentralized autonomy, and performance reporting and management. In this paper we explore the role of object positioning using light-based techniques with an expensive high-end system (IR moCap system) and then how a low cost VLP system could replace it.

A review of current techniques reveals a range of sensor modalities comprised of self-measured and infrastructure-based classes serving different but sometimes overlapping goals. Similarly, the performance needs vary widely in terms of positioning (or tracking) accuracy, number of tracked objects, and speed-complexity (cost). We propose the use of a specific VLP technique that uses active receivers and fixed low-cost infrastructure. We argue that an infrastructure-based positioning system, akin to GNSS for outdoor positioning, is the path forward. With an infrastructure-based system, a multitude of mobile devices can tap into the system and position themselves; a single infrastructure cost is associated across the large number of devices; and computational power is conserved at the mobile device. VLP is an ideal infrastructure to piggyback indoor positioning due to the ubiquity of lighting indoors.

Lastly, we show how a VLP system can be utilized to provide (a) real-time robot control and (b) mirroring in an augmented reality context, for a demonstration application with many mobile targets. Although representative of an I4.0 application, this instantiation is only one of the many ways positioning can impact the upcoming industrial revolution.

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