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Passive Infrared Markers for Indoor Robotic Positioning and Navigation

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Abstract— By using a new materials system, we developed invisible passive infrared markers that can take on various visual foreground patterns and colors, including white. The material can be coated over many different surfaces such as paper, plastic, wood, metal, and others. Dual-purpose signs are demonstrated where the visual foreground is for human view while the infrared background is for machine view. By hiding digital information in the infrared spectral range, we can enable fiducial markers to enter public spaces without introducing any intrusive visual features for humans. These fiducial markers are robust and easy to detect using off-the-shelf near infrared cameras to assist robot positioning and object identification. This can reduce the barrier for low-cost robots, that are currently deployed in warehouses and factories, to enter offices, stores, and other public spaces and to work alongside with people.

***Index Terms*—Passive fiducial markers, near infrared.**

I. INTRODUCTION

There has been a rapid increase in the number of autonomous mobile robots being deployed over the past few years with the total world-wide units surpassing 20,000 in 2018. The majority of these robots have gone into warehouses, distribution centers, and factories. There are relatively few advanced robots that are entering retails stores and other public spaces where they conduct inventory scans, security surveillance, cleaning, and last-mile deliveries. Compared to the robots in the warehouses, most of these advanced robots are much more expensive because they are typically equipped with advanced lidars for positioning and powerful computers for video processing. This is because many of the infrastructure changes that can be made in the warehouses are not allowed in the retail stores and other public places.

Among these infrastructure changes are fiducial markers [1-7] that can be installed in the warehouses to help robots with localization and object identification. Analogous to QR codes, these markers and are typically composed of black-and-white blocks that are designed for robust identification and light-weight computation. Amazon distribution centers, for example, have thousands of these markers on the floors for robot positioning [8]. To use these markers, one just needs to print out a number of different markers from a library using a printer and attach them to various surfaces. A robot equipped with a camera can process the video stream using a low-power computer and identify the markers when one or more of them are in the field of view. The camera pose (i.e., the camera's position) relative to the detected marker(s) can be accurately determined from the captured images. However, due to the unsightly nature of these markers, they have been considered visually intrusive to people and have been shunned by the general public.

There have been a number of proposals to use infrared markers instead that provide less or no visual impact to the environment. Most of these proposals require active infrared illumination. For example, infrared LEDs have been proposed as markers [9]. These require new electrical wiring and are either cumbersome or impractical to deploy. In another example, retroreflective markers are proposed to combine with flashing infrared LEDs on the camera [10]. The infrared LEDs require significant additional power consumption for each robot especially during daytime to compete against the infrared light

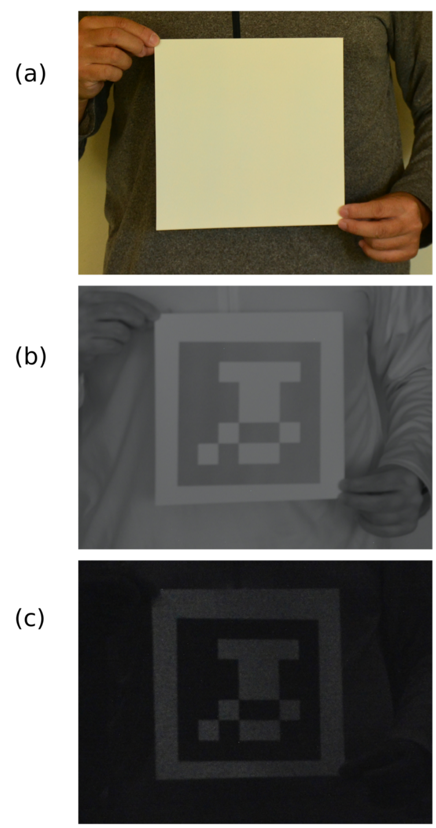

Figure 1. Passive infrared marker coated on a piece of paper. (a) Visible view; (b) image from an infrared camera in daylight; (c) image from an infrared camera under white LED light.

from the ambient. A notable exception is the pioneering work by Yamamiya and coworkers [11] where they used different infrared transparent pigments to create passive invisible markers. Different markers were printed on T-shirts to successfully track the visually impaired. Those markers were hidden in solid color patches with three different foreground colors: yellow, red, and blue. What limited this interesting approach was the inability to create white color using those pigments. This approach only allows patterns where there are no white or light colors in the visual foreground.

In this paper, we report passive infrared markers that are based on a new materials system which allows them to take on various patterns and foreground colors, including white. Figure 1 shows an example where the new material is coated on a piece of paper to form a marker. Analogous to the printed markers, the new infrared marker can be easily attached to various surfaces for robotic applications. The only change to the robot is the addition of an infrared camera. By spectrally shifting the digital patterns to the infrared range, one can hide the fiducial markers in plain sight. This removes one of the hurdles that are currently limiting the robots working in the warehouses from entering the offices and retail stores.

II. Results and discussions

The choice of using the near infrared (NIR) portion of the spectrum for the markers comes from the fact that most image sensors are based on silicon and have spectral response in the NIR. As shown in Figure 2, human vision approximately ranges between 400nm and 750nm while CMOS and CCD sensors are typically sensitive between 350nm and1050nm. The NIR spectral response between 750nm and 1050nm of the image sensors are left unused and have to be filtered out for most cameras. The new materials we have developed for the markers have spectral signatures between 800nm and 1000nm and can thus utilize the existing image sensors with a simple swap of a filter in front of the image sensors.

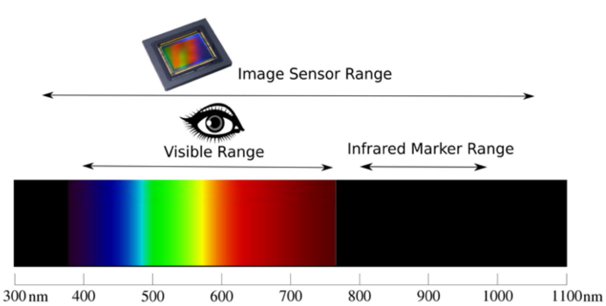

Figure 2. Spectral range of the infrared markers is 800-1000nm compared to the human visible range of 400-750nm.

To enable passive infrared markers that can operate under most ambient lighting conditions, we developed special materials that absorb and reflect/emit infrared light in the dark and bright regions of the markers, respectively. The dark regions of the marker in Figure 1 contain a material that has strong absorption in the NIR. The bright regions of the maker, in contrast, contains a material that has high reflectivity in the NIR and also emits in the NIR when there is visible light in the ambient. In the case when the ambient light has sufficient NIR spectral content (e.g., daylight, incandescent light and fluorescent light), the dark regions on the markers absorb the NIR light while the bright regions reflect the NIR light and thereby makes these regions appear dark and bright on the infrared camera. Notedly, the material in the bright regions of the marker is an infrared phosphor that absorbs a small fraction of the visible light from the ambient, down-converts, and emits in the NIR. In the case when the ambient illumination uses a solid-state light source (e.g., white LEDs) where there is almost no NIR spectral content, the bright regions on the markers appear to glow as viewed by an infrared camera (see Figure 1(c)). This two-component materials design allows the markers to operate under most ambient lighting conditions. Note that these markers can also operate under nominally dark conditions where there are only NIR light sources present. The only condition that these markers do not work is complete darkness when there is no light in either the visible or the NIR spectral range.

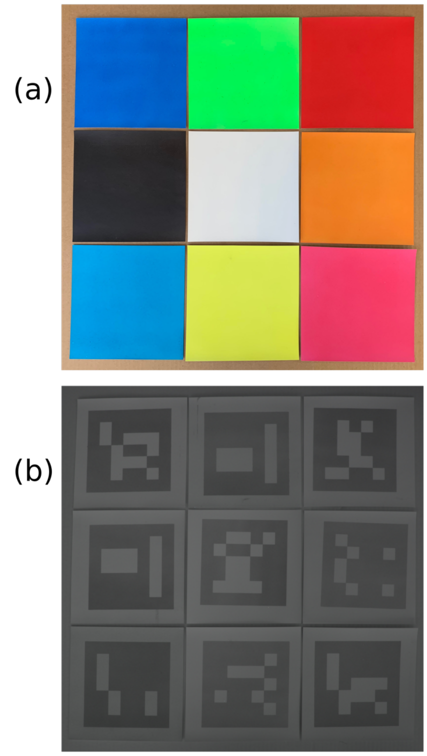

Figure 3. (a) Visible view and the corresponding (b) infrared camera view of infrared markers with different colors.

To allow easy assimilation into different environments, the new infrared markers can take on different foreground colors. By mixing the new materials discussed above with select colorants, the markers can take on blue, green, red, black, white, orange, cyan, yellow, and magenta, as illustrated in Figure 3. Any combinations of these foreground colors can also be obtained. It is therefore possible for the markers to be color-matched with their visual environments and create little or no visual impact to the human eye.

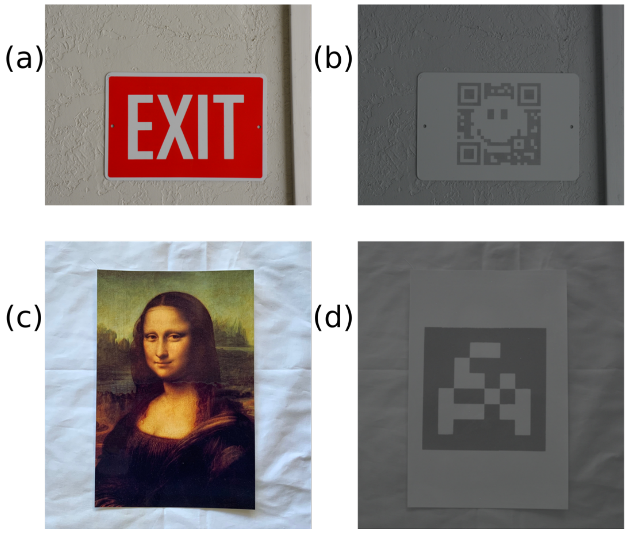

Figure 4. An exit sign and a painting (a) and (c) when viewed by human; (b) and (d) when viewed by an infrared camera.

Furthermore, these infrared markers can take on different visible foreground patterns. Figures 4(a) and 4(b) show a red/white exit sign in the visible foreground with a QR code when viewed through an infrared camera. The substrate in this example is an aluminum plate. Figures 4(c) and 4(d) show a painting in the visible foreground over an infrared marker in the background. These two examples demonstrate that many existing signs, postings, and decorations can be replaced with similar items that serve dual purposes: a visible foreground for people and an infrared background for robots.

The new materials have been formulated into paint to coat over various material surfaces including paper, wood, plastic, metal, ceramic, cotton, and others. Figure 5 shows an example where two ceiling tiles are coated with different infrared markers. Ceiling tiles are widely used in offices, retail stores, and other public spaces. They can be replaced with very little effort. Ceiling tiles pre-coated with various markers therefore provide a convenient option for different users to deploy and adjust the locations of the infrared markers for their applications.

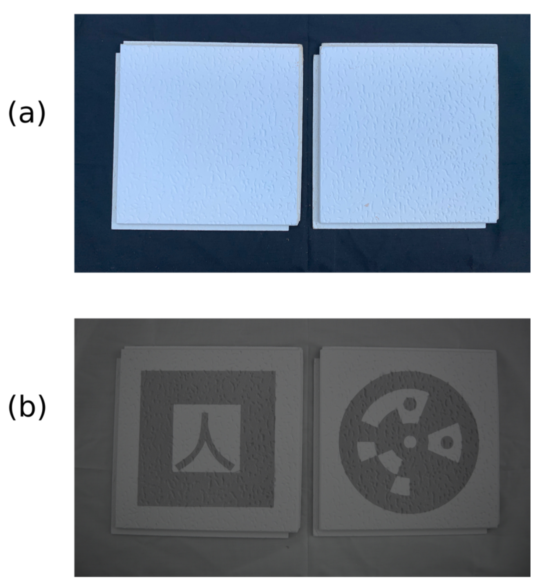

Figure 5. Two coated ceiling tiles: (a) visible view and (b) infrared camera view.

The material used for infrared markers are reliable for more than ten years of operation for typical indoor applications. Most infrared inks that are available today are organic dyes that are not light-fast. They fade over time when exposed to ambient light even in indoor environment. Our own testing shows that these dyes lose their infrared features within a few weeks to a few months under typical indoor lighting conditions. The key components of our infrared materials are inorganic that are far superior in stability. Figure (6) shows infrared images from an on-going reliability testing sample that is stored outdoors under direct sunlight exposure. After six months of outdoor storage, no discernable degradation in contrast is observed between the bright and dark regions of the infrared marker. Given the direct sunlight brightness of 10,000lux and a typical office brightness of 500lux, outdoor storage gives a 20x acceleration for light-fast reliability test for indoor use. This is before we consider the ultraviolet contributions, which is significantly stronger outdoors. Since ultraviolet light is much more damaging to materials than visible light, the acceleration factor is likely higher than 20. Thus, from the current testing results, we can project a lifetime of over 10 years for typical indoor use. We will report updated testing results when additional lifetime data becomes available.

For a robot to utilize these new markers, infrared sensing capability needs to be added. Many of the mobile robots today are equipped with 3D cameras such as Intel RealSense [12].

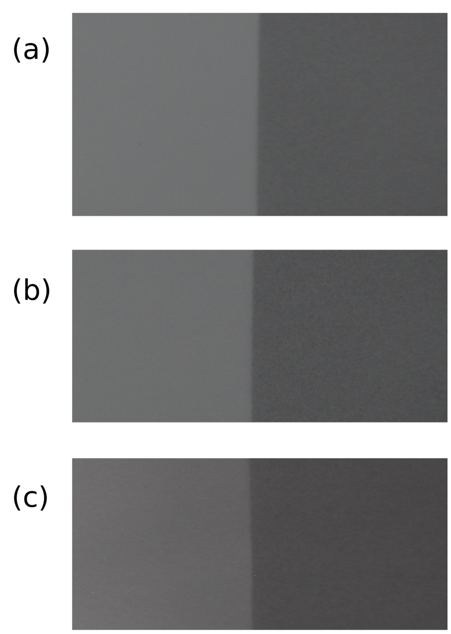

Figure 6: Infrared images of a reliability testing sample placed outdoors under direct sunlight exposure. The left-side of the sample corresponds the bright region of a marker and the right-side corresponds to the dark region. (a) Before any sunlight exposure. (b) After 2 months of sunlight exposure. (c) After 6 months of sunlight exposure.

These 3D cameras have infrared image sensors that combine with infrared laser dot projectors for 3D mapping. Some of these 3D cameras, e.g., RealSense SR305 [13], have infrared-pass filters in front of the image sensors. These can be readily used to detect the infrared markers. It is important to note that some 3D cameras have image sensors that do not have infrared-pass filters. These cameras are not suitable for infrared marker detection because the NIR portion of the signal is overwhelmed by the visible portion. An alternative to using these 3D cameras is to use a separate infrared camera. There are image sensors that have been developed to have high NIR sensitivity [14,15]. These image sensors can be used with the addition of NIR-pass filters to remove the visible light. In cases where one still needs the color information from the cameras, one can replace the existing RGB camera with an RGB-IR camera that is capable of sensing both the visible and the NIR spectral ranges simultaneously. This is achieved by using special RGB-IR images sensors [16, 17] that have been adopted by security surveillance cameras and virtual reality goggles [18].

Marker designs and detection algorithms have been well-developed and are readily available in the public domain [19, 20]. Figure 7 shows the result of marker detection using the existing AprilTag software. No changes to the image processing pipeline were made. The image in Figure 7 was captured when the camera was 25cm away from the marker, which is 18cm in size. We did a series of tests by moving the camera away from the marker. The marker can be detected at more than 3m away, which is close to the ceiling height of typical offices.

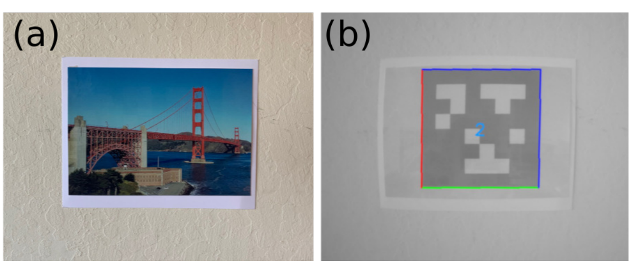

Figure 7. An example of infrared marker detection. (a) Visible view captured by a regular camera; and (b) the corresponding infrared view captured by an infrared camera where the marker is successfully detected and outlined in color. The particular marker used is AprilTag Tag36h11-00002.

By using these infrared markers, one can solve some of the immediate problems that are currently facing the robot developers. For example, on can place infrared markers near the forbidden zones for robots including stairs and escalators. One can also put infrared markers on the robot charging stations for precision docking. These markers can replace some of the existing signs with the identical appearance of the current signs. One additional benefit of these infrared markers is that they can be detected in nominally dark ambient such as a theater. Infrared lights can be used to illuminate the scene and allow robots to detect the markers and navigate in the darkness without disrupting the audience. When the infrared materials are manufactured at large scale, the building surfaces in public spaces can be coated with markers to function as landmarks for robots. These markers can serve as an important component of a general-purpose indoor positioning system not only for robots but also for hand-held devices and smart glasses.

III. Conclusion

Passive infrared markers are introduced for the first time that, analogous to the black-and-white visible markers, can enable easy-to-deploy and low-cost indoor positioning system for robots. These infrared markers are based on a new materials system that contain two key components: one component that selectively absorbs the NIR light and another component that not only reflects NIR light but also absorbs a portion of the visible light and re-emits in the NIR. This complimentary materials design enables the passive infrared markers to operate under most ambient lighting conditions including under white LED light sources where there is little NIR spectral content. These infrared markers can take on a wide range of visible colors and patterns to allow easy assimilation into the working and living environments. They can be integrated into buildings through the forms of ceiling tiles, floor tiles, signs, paintings, wallpapers, wall paints, etc. The surfaces of future buildings and objects can have a visible appearance for people and a digitized bright/dark appearance for robots.

References

[1] H. Kato, M. Billinghurst, "Marker Tracking and HMD Calibration for a Video-Based Augmented Reality Conferencing System", *Proc. 2nd Int'l Workshop Augmented Reality*, 1999, pp. 85-94.
[2] M. Fiala, "ARTag, a Fiducial Marker System Using Digital Techniques", *CVPR '05 Proceedings of the 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, 2005, Vol. 2, pp. 590-596.
[3] E. Olson, "AprilTag: A robust and flexible visual fiducial system", *Proceedings of the IEEE International Conference on Robotics and Automation*, 2011, pp. 3400-3407.
[4] J. Wang, E. Olson, "AprilTag 2: Efficient and robust fiducial detection", *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2016, pp. 4193-4198.
[5] T. Krajnık, M. Nitsche, J. Faigl, P. Vanek, M. Saska, L. Preucil, T. Duckett, M. Mejail, "A Practical Multirobot Localization System", *Journal of Intelligent & Robotic Systems*, 76, 2014, pp. 539–562.
[6] S. Garrido-Jurado, R. Muñoz-Salinas, F.J. Madrid-Cuevas, R. Medina-Carnicer, "Generation of fiducial marker dictionaries using mixed integer linear programming", *Pattern Recognition*, 51, 2016, pp. 481-491.
[7] F. J.Romero-Ramirez, R. Muñoz-Salinas, R. Medina-Carnicer , "Speeded up detection of squared fiducial markers", *Image and Vision Computing*, vol. 76, 2018, pp. 38-47.
[8] R. D'Andrea, P. K. Mansfield, M. C. Mountz, D. Polic, "Method and system for transporting inventory items", US Patent US008170711B2, 2012
[9] M. Faessler, E. Mueggler, K. Schwabe, D. Scaramuzz, "A Monocular Pose Estimation System based on Infrared LEDs", *IEEE International Conference Robotic Automation*, 2014, pp. 907-913.
[10] Y. Nakazato, M. Kanbara, N. Yokoya, "Localization of wearable users using invisible retro-reflective markers and an IR camera", *Proc. SPIE Electronic Imaging*, Vol.5664, 2005, pp. 563-570.

[11] S. Yamamiya, H. Makino, M. Hirono, Y. Maeda, I. Ishii, “Using infrared-transparent pigments to identify objects”, *Systems and Computers in Japan*, 2002, Vol. 33, pp. 74-82.
[12] https://www.intel.com/content/www/us/en/architecture-and-technology/realsense-overview.html
[13] https://www.intelrealsense.com/depth-camera-sr305/
[14] https://www.sony-semicon.co.jp/e/products/IS/security/technology.html
[15] https://www.ovt.com/purecel-pixel-tech/nyxel-technology
[16] https://www.ovt.com/purecel-pixel-tech/rgb-ir-technology
[17] https://www.canonnews.com/canon-adds-5-new-image-sensors-to-its-product-list
[18] https://www.extremetech.com/gaming/288064-oculus-launches-rift-s-399-fewer-cameras-higher-res-lenses
[19] https://github.com/AprilRobotics/apriltag_ros
[20] https://github.com/pal-robotics/aruco_ros