Sensor Fusion for Ecologically Valid Obstacle Identification: Building a Comprehensive Assistive Technology Platform for the Visually Impaired

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***Abstract*—Sensor fusion represents a robust approach to ecologically valid obstacle identification in building a comprehensive electronic travel aid (ETA) for the blind and visually impaired. A stereoscopic camera system and an infrared sensor with 16 independent elements is proposed to be combined with a multi-scale convolutional neural network for this fusion framework. While object detection and identification can be combined with depth information from a stereo camera system, our experiments demonstrate that depth information may be inconsistent given material surfaces of specific potential collision hazards. This inconsistency can be easily remedied by supplementation with a more reliable depth signal from an alternate sensing modality. The sensing redundancy in this multi-modal strategy, as deployed in this platform, may enhance the situational awareness of a visually impaired end user, permitting more efficient and safer obstacle negotiation.**

I. Introduction

There are 285 million people suffering from visual impairment worldwide with 39 million blind and 246 million with low vision [1]. The economic impact is estimated to have approached $3 trillion dollars globally in 2010 [2] with conservative estimates approaching $75 billion dollars per annum in the United States alone [3], [4]. While therapeutic advances are under development for a number of conditions, there are a multitude of causes that still engender severe visual disability [5], [6]. Additionally, many of these conditions are on the rise [7]. This is only compounded by the fact that children born premature are now surviving at increased rates, a remarkable advance, but one that renders more in need with blindness, as retinopathy of prematurity is increasing significantly [8], [9]. The most unsettling of these facts are the associated increases in mortality and morbidity [10]–[12], which is sadly contributed to by increases in suicide [13]–[15].

Impaired object detection and spatial perception secondary to vision loss constrain one's mobility [16]–[18]. This inevitably leads to issues with unemployment [19], quality of life losses [20]–[22], and functional dependencies [23] that limit psychosocial wellbeing [24]. Current tools offered to support continued mobility following visual impairment are designated within two classifications: primary and secondary aids. Primary aids are the foundation of a mobility solution platform to help restore independence following the tragic loss of sight, whereas secondary aids are used to help augment the safety profile of primary tools. While all three primary mobility tools, the white cane, the guide dog, and the adaptive mobility device (AMD) [a modified cane platform] offer improved navigation for those with a compromised visual system, each of these tools has well-known weaknesses [25]–[32]. The white cane has difficulty with edge detection (e.g., curbs) and obstacle detection, neuromusculoskeletal overuse injuries and syndromes, training requirements, training retention/education, and cognitive burden. Whereas the guide dog and the AMD, a rectangular, cane-like walking frame with a simpler push and clear strategy for use, simply do not represent tenable solutions for many, either due to the care and attention animate companions require or due to poor maneuverability in cluttered environments [28], [33]–[49].

Although significant training periods and the esoteric nature of many current devices are challenges, the issues can certainly be addressed. To start, it is critical that the limitations of devised ETAs be highlighted and pinpointed, garnering essential information for the design and mechanics of an idealized tool. These limitations include: 1.) very narrow fields of view and/or limited ranges [50], [51], requiring the end user to employ compensatory techniques to maximize usefulness, 2.) the masking of auditory cues by re-displayed environmental information binaurally through headphones or earbuds [52], [53], blocking crucial environmental signals that many visually impaired are depending on for safe navigation, 3.) integration directly into primary mobility devices such as the white cane [54]–[56], creating an unstable foundation for mapping, especially given inconsistencies in cane technique, 4.) a dependence on only one sensor mode or type of sensor system [57], [58], each of which has inherent flaws given environmental constraints (for example, most infrared sensors work poorly in bright sunlght), 5.) deployment in hand-held units which preclude manual motor interaction [59], [60], especially problematic for protection during unanticipated trips and falls, 6.) coded displays of the environment through an intact sense in non-intuitive fashions [61]–[64], often necessitating significant training periods before these coded signals can be learned and interpreted, 6.) poor aesthetics or the conspicuous and very obvious nature of the device when worn, leading to self-consciousness during use [61], [64]–[67], and/or 7.) significant financial cost, leading to devices that are prohibitively expensive.

The objective of this study was to leverage sensor fusion between a LIDAR-based time-of-flight sensing modality and stereoscopic cameras for ecologically valid obstacle identification, as a foundational step towards building a comprehensive assistive technology platform for the visually impaired.

II. Method

A. ZED camera for stereo image matching

General camera can capture sequences of RGB image with color value. By combining two spatially offset (e.g., left and right) images, we can match multiple points between two images from left and right image channels for generating additional information as a depth channel. The stereo camera we use is Stereolabs ZED$^{\text{TM}}$ camera, which can capture up to 2.2K high resolution and up to 100 high frame rate 3D video. Depth up to 20m can be measured in indoor and outdoor use. ZED$^{\text{TM}}$ camera comes with a detailed API which enables us to call for rendering real time depth image.

B. Sensor data fusion framework

Fig. 1. The sensors arranged together vertically.

As is generally known, the stereo camera is sensitive to visible light and cannot generate reliable depth information in low-visibility scenarios such as night, or during rain and snow. To deal with low-visibility scenarios, we use the infrared (IR) sensor from LeddarTech$^{\text{TM}}$ in conjunction with the stereo camera. The IR sensor module combines 16 independent active elements into a single sensor, resulting in rapid, continuous and accurate detection. It has a detection range up to 100 meters, and 9° to 95° beam options for optimized field of view. The IR sensor measures depth by emitting pulses of infrared light, using a photodetector to capture the reflected pulses, and then digitally converting and processing the signal to assess the presence and position of objects in its field of view. Since each measurement is made from thousands of discrete light pulses, the infrared sensor is able to obtain reliable measurements in rain, snow, fog or dust which is problematic for stereo camera to detect. So we process the sensor fusion as shown in Figure 1. We arrange the stereo camera close to the IR sensor to minimize the difference between two sensors' fields of view.

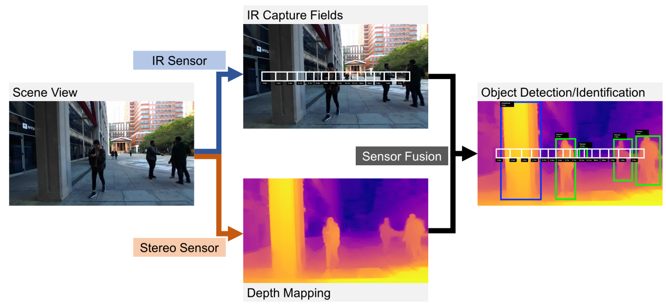

Fig. 2. Sensor fusion framework.

As shown in Figure 2, the IR sensor detects distance values as an array for each of 16 independent segments. Those values are mapped back to the image captured by the stereo camera. Since the IR sensor detects object distances based on the reflected infrared, if the object is further than the effective range, no value will be returned for this segment. In such situations, we will use depth from the stereo camera as distance value. Otherwise, our fusion algorithm will merge the two values from the two sensors and fairly give higher weight to which from IR sensor. Then we can get fused and reliable depth information for those 16 segments.

C. Deep learning for object detection

We use a multi-scale convolutional neural network based architecture because of its relatively low time complexity and good accuracy. The architecture performs well because object proposal is done at four different scales by the network efficiently. The other advantage of this network is that everything including features, proposals and detection are learned end to end which makes the network relatively fast. The time complexity of the network is not constrained by separate object proposals and detection networks.

As shown in Figure 3, our architecture is a single unified network consisting of a main trunk and four different proposal sub-networks connected to it at different scales in addition to the detection network. The network detects objects at four different scales. The region proposal network outputs a set of rectangular object proposals with their objectness score (class probability). The idea behind using multiple proposal networks at different scales is that object proposals at multiple receptive fields are obtained by the network. The first proposal subnetwork consists of a convolution layer (since the sub-network is close to lower layers of convolution of the main trunk which may cause instability due to the sub-network being closest to the main trunk), followed by a detection layer

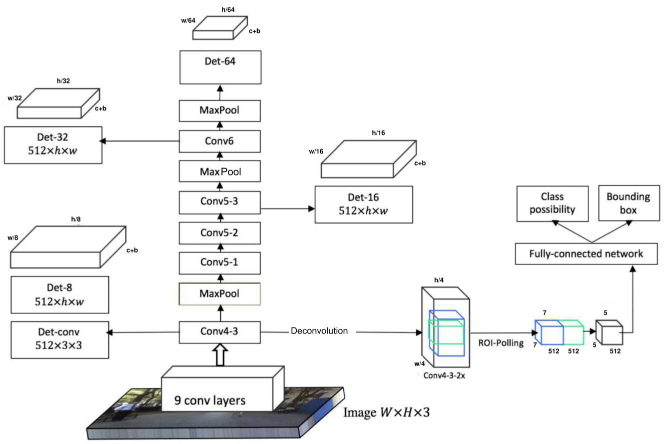

Fig. 3. Network architecture for object detection in RGB domain.

which maps the convolution map into a fixed feature vector. These feature vectors are fed to two fully connected networks which outputs class of the detection and the proposal bounding box coordinates. The three other proposal sub-networks have similar detection layers which output the class of the detection and its corresponding bounding box coordinates. The proposals are given by the sliding window paradigm. The proposal network itself can be used as a detection network but does not perform as well. Thus, a separate detection network is introduced.

The object detection sub-network consists of a deconvolution layer in order to increase the resolution of the feature map. The deconvolution layer upsamples the features from the Conv4-3 layer as shown in Figure 3. Feature upsampling does not increase the memory and time complexity of the network significantly but rather boosts detection performance of small objects. The outputs from the proposal sub-networks are used to perform region of interest pooling with context for the detection sub-network. Context has been shown useful for object detection. We take the context nearby the proposed object into account and evaluate the features of the anchors obtained from deconvolved feature maps. The features are obtained from anchor at two different scales and concatenated as shown in Figure 3. The context anchor is 1.5 times larger than the proposal network anchor. These concatenated features are passed through a convolution network to halve the number of feature maps and reduce the number of parameters. These feature maps are passed through a fully connected network which outputs the class probability and bounding box coordinates for the corresponding region of interest.

III. Experiment

We use our sensor fusion framework as shown in Figure 1 for object detection in indoor and outdoor environments. We carry the fixed sensors as shown in Figure 1 with a portable battery source and save RGB image data, depth information from stereo camera and distance values from the IR sensor simultaneously for several 10 seconds clips. Figure 4 and

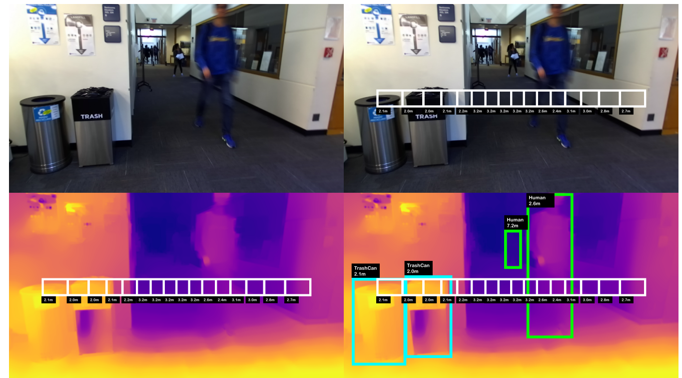

Fig. 4. Indoor object detection using sensor fusion.

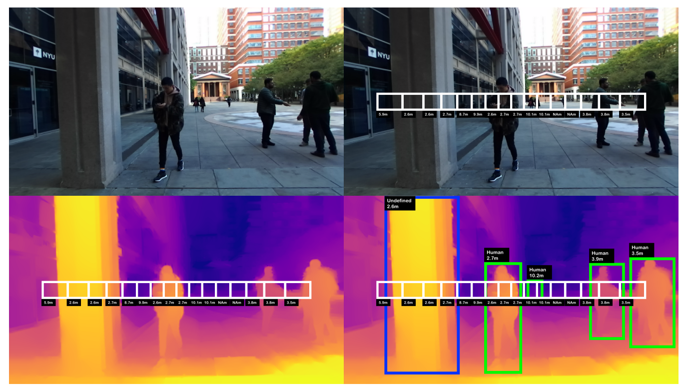

Fig. 5. Outdoor object detection using sensor fusion.

Figure 5 show the raw RGB image (on the upper left), and the distance array detected by the IR sensor, bounded in 16 boxes horizontally. The size of each box in the image is exactly calculated by the physical parameters of the IR sensor and the stereo camera. Those distance values are then fused with the depth image from the stereo camera as shown in the lower left. We use a more consistent colormap to render depth image where light yellow corresponds to objects nearer to the sensor and dark purple corresponds to objects that are further away. Our object detection network can not only recognize general objects, but as shown by the blue bounding box in the lower right of Figure 5, it can detect obstacles in near environment like the structural column. The column was detected by the IR sensor even it was not one of the objects in our training set.

Besides, in the lower panel of the indoor environment in Figure 4, the right trash can has inconsistent color with light yellow at the top and dark purple at the bottom. From the raw RGB image, we can determine that this is a result of the polished surface of the body. Although this trash can has consistent distance value from the sensor, the stereo camera failed to output a reliable depth image for it. However, from the range value of the IR sensor, the polished surface does not present a problem. In such situations, it can provide reliable distance information to help remove the inconsistency of depth inferred from the stereo images. By this robust fusion framework, all front objects in the sensor's field of view will be effectively detected, mapped to depth image and conveyed to user for improved navigation. Those objects will be labeled as one of the categories from the training samples or as general obstacles.

IV. Conclusion

We have presented a sensor fusion framework for an electronic travel aid (ETA) or a Smart Service System for spatial intelligence and on-board navigation that has the potential to provide real-time situational and obstacle awareness in one's immediate environment, allowing blind and visually impaired individuals to travel more safely in three-dimensional (3D) space. While the strengths of a stereo camera system are substantial, there are limitations and these need to be accounted for in a comprehensive assistive technology platform with significant ecological validity. Multimodal approaches as delineated above represent a powerful first step towards wearable devices that may supplement existing tools in their core functionality or create new categories in themselves.

Our current and future work hinges on taking this framework (hardware/software) and integrating it into a wearable vest that benefits from the multimodal integration strategy as described above, inclusive of distance/ranging plus image sensors, extracting pertinent information about obstacles in the environment. We have also initiated work with novel "re-displays" of this environmental information through both haptic interfaces (torso-based belts that actuate spatially preserved obstacle-pertinent, spatial information) and audiologic interfaces (headsets that contain binaural bone conduction transducers (speakers), leaving the ear canal open for air conduction, and inclusive of microphones for oral communication.

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