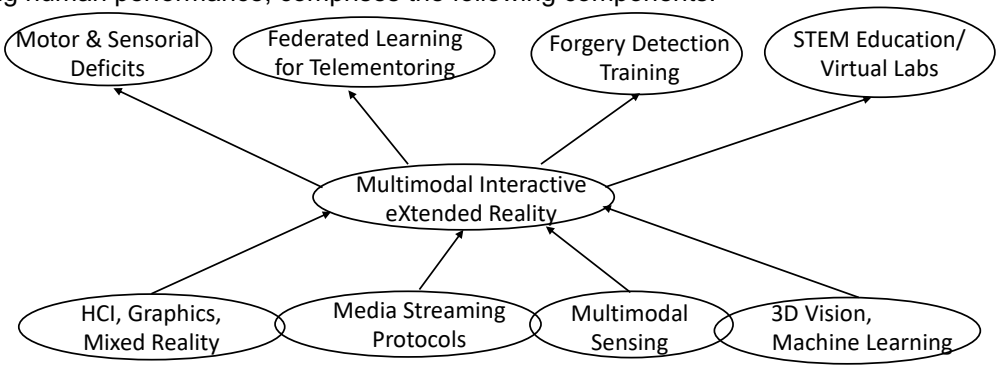
Multimodal, Interactive eXtended Reality (MIXR) for Understanding and Quantifying Human Interactions and Performance - **Prabha (Balakrishnan) Prabhakaran**

With my multi-faceted experience in inter-disciplinary research, managing large research programs and federal public policy, I am working on ***Multimodal, Interactive eXtended Reality (MIXR)*** for understanding and quantifying human performance. Understanding and quantification of human performance can in turn help in multiple ways: better human-computer interaction (HCI), improved training, rehabilitation, adaptive techniques to overcome deficit sensorial perceptions (such as phantom pain, speech, and hearing impairments).

I started my funded research from a database perspective of storing and retrieving human motion sequences, through my NSF (USA National Science Foundation) CAREER Award on Animation Databases. Subsequently, I worked on 3D tele-immersion and collaborative mixed reality (MR) systems, by incorporating networking aspects such as Quality of Service (QoS) requirements and Quality of Experience (QoE) for multimodal streaming. Using the data generated from human interactions in these MR systems, I addressed human motion/gesture understanding/quantification from multiple aspects: (a) gait analysis and gesture recognition; (b) limb motions in stroke-patients and amputees; (c) tongue motion for speech production (especially stroke afflicted persons), and (d) lung tumor motion for profiling human breathing nature and facilitating effective radiation treatments. For understanding human motions/gestures, I worked on various aspects of body sensor data analyses: multi-factor analysis (MFA), fuzzy clustering, association rule mining, and supervised machine learning. Recently, I have been working on synthetic data generation, deep learning (DL), explainability of DL models (used for body sensor data), and core set selection based on explainability metrics. Addressing this problem of human performance quantification, I have explored various approaches and application domains. Along the way, I found the possibilities for malicious tampering of human performance data and the associated risks, prompting me to work on the forensics of multimodal/multimedia human performance data.

With this background, the proposed ***Multimodal, Interactive eXtended Reality (MIXR)*** for understanding / quantifying human performance, comprises the following components.



Proposed Multimodal, Interactive eXtended Reality (MIXR) and its Application Domains

1. MIXR for Motor & Sensorial Deficits:

My research group has used 3D motion capture systems, on-body sensors such as EMG to build MIXR systems. By using 3D / RGB-D cameras that capture both RGB (normal 2D video) and depth information, our research facilitates real-time generation of 3D video avatars (i.e., "live" 3D models of human in the real-world scene) that can interact with objects in the virtual world. These objects in the virtual world can be 3D computer graphics generated; they can also be other 3D video avatars of humans in remote sites, thereby providing a collaborative immersive environment. For multimodal interactions, we have used different types of sensors such as high-stiffness haptic devices, vibro-tactile sensors, accelerometers, gyroscopes, etc.

Deploying MIXR Systems for Healthcare: We have successfully deployed some of our MIXR-based systems in healthcare domains such as:

- **Physical Medicine & Rehabilitation:** We developed novel approaches for force enhancement and delay compensation, to handle Just Noticeable Difference (JND) in force perception (for stroke patients with muscular weaknesses) and to handle stochastic delay variations in Internet communication of haptic data. This system (https://youtu.be/mVc-fa_Ytso) was used to remotely diagnose the problems in 15 patients with upper-arm disabilities in the Dallas Veterans Affairs (VA) Hospital. (The doctor was in the city of Richardson, TX and the patient was in the city of Dallas, TX at Dallas VA). The results of this remote diagnosis showed high degree of correlation with in-person diagnosis of these patients.
    - Annaswamy, T.M., Prabhakaran, B., Desai, K., and Khargoankar, N.A. "VIRTEPEX: Virtual Remote Tele-Physical Examination System", U.S. Provisional Patent Application No.: 63/351,671, June 13, 2022.
- **Managing Phantom Limb Pain:** Phantom Limb Pain or simply, Phantom Pain is a severe chronic pain that is experienced as a vivid sensation of the pain in missing body part. Epidemiological studies obtained from a large sample indicate that the short-term incidence rate of the phantom limb pain is 72%, while long-term incidence rate (6 months after amputation) is 67%. In the work presented in ACM Multimedia 2017 & 2019 (https://youtu.be/5Fjud10gEzQ, https://youtu.be/JMO4MIav34w), we proposed a novel Mixed Reality based system for MAnaging Phantom Pain (Mr.MAPP) using the 3D video avatars of the amputees. In this system, an illusion of the virtual limb is created in real-time by mirroring the patient's symmetric anatomical limb in the captured data with the help of various computer vision and graphics techniques. (ACM (Association for Computing Machinery) awarded "Results Replicated" badge for the work on software for phantom pain management after testing by a third party in Europe).
    - Annaswamy, T.M., Prabhakaran, B., and Chung, Y.Y., "High Fidelity Mixed Reality System for Managing Phantom Pain", U.S. Provisional Patent Application No.: 63/325,410, Mar 30, 2022.
- **Speech Impairments**: Opti-Speech is an interactive system that integrates tongue, lip, and jaw motion capture from 3D Electromagnetic Articulography (EMA) systems to animate a 3D tongue model (https://youtu.be/r9NwcDlqAMU). Persons with speech impairments get real-time visual feedback of their tongue and jaw movements during speech therapy, which helps both them and the speech therapist to guide correct tongue positioning for speech sounds.
    - "Opti-Speech", Technology Licensed to Vulintus Inc., by the University of Texas, Dallas. https://www.vulintus.com/optispeech *Inventors:* B. Prabhakaran, Thomas Campbell, Eric Farrar, William Katz, Robert Rennaker, Jennell Vick, and Jun Wang; Opti-speech is being used in the school districts in Cleveland, OH and Dallas, TX.

2. In-home / Remote Activity and Physiological Monitoring: We have deployed various types of body sensors for in-home and remote human activity monitoring and worked on various aspects of body sensor data analyses: multi-factor analysis (MFA), fuzzy clustering, supervised machine learning, and personalized rehabilitation. These studies involved sensor deployment in the patients' home (following IRB (Institutional Review Board) protocols). Sensor-based in-home activity monitoring also served as a valuable digital diary, compensating for the inaccuracies in patient's self-reported activities.

- "Using Biometric Technology for Telehealth and Telerehabilitation", Thiru M Annaswamy, Gaurav N Pradhan, Keerthana Chakka, Ninad Khargonkar, Aleks Borresen, B. Prabhakaran, Physical Medicine and Rehabilitation Clinics (Elsevier Publications), 32 (2), 437-449, May 2021. https://www.sciencedirect.com/science/article/pii/S104796512030111X.
- "Personalized 3D exergames for in-home rehabilitation after stroke: a pilot study", Kevin Desai, B. Prabhakaran, Nneka Ifejika, Thiru M AnnaswamyDisability and Rehabilitation: Assistive Technology, (Taylor & Francis Publishers), 1-10, April 2021.
- "Association Rule Mining in Multiple, Multidimensional Time Series Medical Data", G.N. Pradhan and B. Prabhakaran, Journal of Healthcare Informatics Research (Springer), Volume 1, Issue 1, June 2017, pp. 92-118.
- "Discovering Multidimensional Motifs in Physiological Signals for Personalized Healthcare", A. Balasubramanian, J. Wang, and B. Prabhakaran, IEEE Journal of Selected Topics in Signal Processing, Volume 10, Number 5, August 2016, pp. 832-841.

- "A Body Sensor Network with Electromyogram and Inertial Sensors: Multi-modal Interpretation of Muscular Activities," H. Ghasemzadeh, R. Jafari, and B. Prabhakaran, IEEE Transactions on Information Technology in Biomedicine, Vol. 14, No. 2, pp. 198-207, March 2010.
- "Analyzing and Visualizing Jump Performance Using Wireless Body Sensors", G.N. Pradhan and B. Prabhakaran, *ACM Transactions on Embedded Computing Systems*, Volume 11, Issue S2, Article No. 47, August 2012.
- "Exploring unconstrained mobile sensor-based human activity recognition", Luis Gerardo Mojica de La Vega, Suraj Raghuraman, Arvind Balasubramanian, Balakrishnan Prabhakaran, Proceedings of 3rd International Workshop on Mobile Sensing, Co-located with IEEE IPSN'13 and CPSWEEK, April 8, 2013, Philadelphia, PA, USA.

***3. MIXR-based Systems for Education*:** We developed collaborative virtual chemistry laboratory using our multi-modal 3D immersive platform. Two different Chemistry experiments – hydrometer-based measurement and measurement without parallax error – were deployed (https://youtu.be/rJmoreMK0RU). Students at Dallas County Community College District (DCCCD) have started using this laboratory. For Botany students, we designed MIXR-based framework that facilitates active learning through an interactive, virtual nature walk (https://youtu.be/ie9TMDKZ750). The nature walk environment consists of 7 virtual trees: Maple, Oak, Horse Chestnut, Western White Pine, Coconut Palm, Red Cedar, and White Ash. Each of the trees belongs to a classification in the tree taxonomy. We developed HTN-A (Hierarchical Task Network for Assessment) that can not only model the tasks efficiently but can also incorporate the assessment logic into virtual laboratory experiments. We also provide an authoring script which can be used by the teachers to automatically generate the HTN-A.

Virtual nature walk offers several advantages: (i) persons with physical disabilities can participate and learn; (ii) nature's seasonal effects can be taught to students irrespective of the semester in which the course is taught. This virtual nature walk was demonstrated in the Super Computing 2019 (SC'19) conference with participants from Denver, CO, Dallas, TX and Tokyo, Japan, resulting in a trans-Pacific demonstration (https://cs.utdallas.edu/trans-paci%ef%ac%81c-mixed-reality-plant-walk/).

***4. Multimodal / Multimedia Forensics, Security, and Authentication*:** My research in human performance analysis using multi-modal sensory data gave critical insights into how data could be modified/forged, raising concerns regarding cyber security trust and authentication. Considering that multimodal data sources are typically being used for several purposes (from authenticating access privileges to decision making as in autonomous vehicles (AVs)), tamper detection, estimation of risks and threats become a necessity. A wide range of applications such as vehicle automation and robot navigation are highly dependent on 3D LiDAR data for perception and decision-making. Research studies have exposed its vulnerabilities making it crucial to authenticate the data before its employment. We have designed ALERT (Authentication, Localization, and Estimation of Risks and Threats), that provides additional security for navigation and control of remotely operated vehicles and robots by tamper-proofing 3D LiDAR data, using an innovative mechanism that creates and extracts a dynamic watermark, detects tampering, and estimates the level of risk and threat based on the temporal and spatial nature of the attacks.

In the paper under review for IEEE Transactions on Instrumentation and Measurement, we have proposed a Vision-Based Measurement (VBM) system that can compute the probability of forgery for each pixel in the image and predict the tampered area ultimately. This VBM is a deep learning model, trained on FDL-Net (*Forgery Detection and Localization Network*) that works on 2D images to detect forgery at pixel level and localize the image area under attack. Based on the localized mask generated by FDL-Net, we localize the region under attack in the 3D LiDAR point cloud corresponding to the attacked region in the 2D images. The localized region in the LiDAR data is used to estimate the distance of the forged object from the AV. Some publications related to this activity:

- "Near Real-Time Forgery Detection and Localization in Stereo RGB and 3D LiDAR Data from Autonomous Vehicles", S. Mohammadpour, S. Dakshit and B. Prabhakaran, Under review, IEEE Transactions on Instrumentation and Measurement. (Also available as Tech Report: UTDCS-02-21 - https://cs.utdallas.edu/wp-content/uploads/2021/02/FDL-Net.pdf)
- "Reinforcement Learning Framework for Navigation problems using LiDAR Scan-Based Virtual Reality", Sagnik Dakshit, Hiranya Kumar, Chris Young Jin Jung, Ammar Hasan-Mehboob Nanjiani,

Marshal Renfrow, Brian To, Briscoe Fletcher, Liam Heffernan, and Balakrishnan Prabhakaran, Machine Learning for Mobile Robot Navigation in the Wild (ML4NAV) Symposium as part of the AAAI Spring Symposium Series 2021. (Peer-reviewed Short Paper).

- "ALERT: Adding a Secure Layer in Decision Support for Advanced Driver Assistance System (ADAS)", K. Bahirat, U. Shah, A. Cardenas, and B. Prabhakaran, Proceedings of 26th ACM Multimedia 2018, Seoul, Korea, October 2018.
- "ADD-FAR: attacked driving dataset for forensics analysis and research", Kanchan Bahirat, Nidhi Vaishnav, Sandeep Sukumaran, B. Prabhakaran, MMSys 2019: 243-248, Amherst, MA, USA.
- "A Study on LiDAR Data Forensics", K. Bahirat and B. Prabhakaran, *Proceedings of the IEEE International Conference on Multimedia and Expo (ICME'17),* Hong Kong, July 2017.
- "Spectral Watermarking for Parameterized Surfaces," Yang Liu, Balakrishnan Prabhakaran, Xiaohu Guo, in IEEE Transactions on Information Forensics and Security, Vol. 7, No. 5, 2012, pp.1459-1471.

5. MIXR and Psychological Perceptions:
Through a cooperative agreement with psychologists in the US Army Research Laboratory (ARL), we are currently developing a research-grade prototype system called Collaborative Adaptive Augmented Reality Environment (CAARE) to investigate the trade-offs for human performance with real-time, dynamic AR (Augmented Reality) information. This research examines how a participant's perceptions of factors such as depth/distance in mixed reality environments are influenced by parameters such as color and speed of objects, and how these perceptions affect decision-making in field exercises and other training scenarios.

Federal public health policy and administrative experiences: My current experience and exposure as NSF (National Science Foundation) Program Director includes administrative leadership positions: (a) Co-Lead of Smart and Connected Health (SCH) in cooperation with NIH (National Institute of Health); (b) Theme Lead for National AI Institutes on Human-AI Interaction; (c) Co-Chair of Future of Work at the Human-Technology Frontier (FW-HTF), one of the NSF's Big Ideas programs. Currently, I am involved in programs such as National AI Institutes on the theme "Intelligent Agents for Next-Generation Cybersecurity" and "Trustworthy AI". Apart from these, I have been participating in large initiatives such as STC (Science and Technology Center) and SaTC (Secure and Trustworthy Cyberspace) Frontiers, NSF's nation-wide Cybersecurity programs.
From a public health policy perspective, I am serving as a Member of the Interagency Working Group (IWG), Digital Health Research & Development (DHRD) (https://www.nitrd.gov/coordination-areas/dhrd/; formerly, Health Information Technology Research & Development). DHRD membership is restricted to Federal employees from 15 agencies such as NSF, NIH, NIST, and helps coordinate research activities in the broad healthcare arena.

Experience with Inter-disciplinary Collaborations: My track record in establishing partnerships across disciplines and institutions complements my research contributions. My research spans multiple areas such as multimedia databases, networking, computer vision, graphics, robotics, biomedical sensing, and HCI (Human-Computer Interaction). Hence, throughout my research career, I have been collaborating with researchers from various disciplines: mechanical/biomedical engineers, Physical Medicine & Rehabilitation, Speech Pathologists, Psychologists, Oncologists/Medical Physicists, as well as researchers from Arts, Technology, and Emerging Communication (ATEC) in UT Dallas. I have been actively collaborating with other institutions such as Dallas Veterans Affairs Medical Center (DVAMC) and the University of Texas Southwestern Medical Center. For some of these collaborations, I have held formal joint appointments as well. For instance, I have Work Without Compensation (WOC) appointment at the DVAMC and an Affiliate Faculty appointment with the UT Dallas Bio-Medical Engineering Department (details are in my CV).