SPIE Medical Imaging 50th anniversary: historical review of the Image-Guided Procedures, Robotic Interventions, and Modeling conference

Jeffrey H. Siewerdsen[a,b,*] **and Cristian A. Linte**[c]
[a]Johns Hopkins University, Department of Biomedical Engineering, Baltimore, Maryland, United States
[b]University of Texas MD Anderson Cancer Center, Department of Imaging Physics and Institute for Data Science in Oncology, Houston, Texas, United States
[c]Rochester Institute of Technology, Department of Biomedical Engineering, Rochester, New York, United States

Abstract

Purpose: Among the conferences comprising the Medical Imaging Symposium is the MI104 conference currently titled Image-Guided Procedures, Robotic Interventions, and Modeling, although its name has evolved through at least nine iterations over the last 30 years. Here, we discuss the important role that this forum has presented for researchers in the field during this time.

Approach: The origins of the conference are traced from its roots in Image Capture and Display in the late 1980s, and some of the major themes for which the conference and its proceedings have provided a valuable forum are highlighted.

Results: These major themes include image display/visualization, surgical tracking/navigation, surgical robotics, interventional imaging, image registration, and modeling. Exceptional work from the conference is highlighted by summarizing keynote lectures, the top 50 most downloaded proceedings papers over the last 30 years, the most downloaded paper each year, and the papers earning student paper and young scientist awards.

Conclusions: Looking forward and considering the burgeoning technologies, algorithms, and markets related to image-guided and robot-assisted interventions, we anticipate growth and ever increasing quality of the conference as well as increased interaction with sister conferences within the symposium.

 [DOI: 10.1117/1.JMI.9.S1.012206]

Keywords: image-guided interventions; medical robotics; image registration; image visualization; image display; interventional imaging.

Paper 21332SSR received Dec. 22, 2021; accepted for publication Mar. 22, 2022; published online Apr. 18, 2022.

1 Introduction

In its first 50 years, the SPIE Medical Imaging Symposium has provided an outstanding forum for scientific communication from researchers in academia and industry, from students and seasoned luminaries, spanning a tremendous breadth and depth of medical imaging research. The MI104 Image-Guided Procedures, Robotic Interventions, and Modeling conference traces its roots to 1989 and has presented a vibrant forum that has become an important feature on the scientific landscape in North America for researchers with interest in image-guided interventions, surgical robotics, and a variety of clinical applications ranging from surgery and interventional radiology to radiation therapy.

In this paper, we briefly trace the history of the conference and highlight major scientific themes for which it has served as a venue for many scientists to present their work. These

*Address all correspondence to Jeffrey H. Siewerdsen, jsiewerd@gmail.com

include, but are not limited to, topics on interventional imaging [all modalities, including endoscopy, other optical imaging technologies, radiography/fluoroscopy, ultrasound, computed tomography (CT), magnetic resonance (MR), and nuclear medicine imaging], landmark-based, feature-/surface-based, and image-based registration for interventional guidance, surgical robotics, and image display/visualization. Some of the noteworthy highlights are also summarized, including top-cited papers from the conference proceedings and awards earned by students and early-career scientists.

2 History and Evolution of MI104: "The Image-Guided Procedures Conference"

The inception of the MI104 conference now entitled Image-Guided Procedures, Robotic Interventions, and Modeling traces its roots to 30+ years ago on topics of image capture and display. As shown in Table 1, the name of the conference has evolved over time, reflecting emerging themes ranging from image capture, display, and visualization in its first 10 years to themes of image-guided procedures (starting in 2001), modeling (in 2008), and robotic interventions (in 2012).

Since its first stand-alone edition in 1989, the MI104 Image-Guided Procedures conference has grown to become the third- or fourth-largest conference under the SPIE Medical Imaging Symposium umbrella, attracting as many as 150 submissions and close to 400 attendees each year, many of whom are students and early-career scientists, and some presenting their research at an international forum for the first time. Well integrated with sister conferences throughout the symposium, the MI104 conference has become the premier forum in North America for presentation of cutting-edge research in image-guided procedures.

In addition to becoming one of the top attended conferences, since the mid-late 2000s, the Image-Guided Procedures conference has hosted joint sessions with several other conferences in the SPIE Medical Imaging Symposium. A joint session with Ultrasound Imaging and Tomography has become a recurring feature for more than a decade, highlighting contributions on ultrasound-guided interventions. Beginning in 2021 were joint sessions with the Imaging Informatics conference focused on research related to interventional workflow optimization and use of phantoms for simulation and validation. New in 2022 were joint offerings with the Physics

Table 1 The title of the conference has changed over the years, reflecting an evolution in major themes, from "image capture and display" in the late 1980s to "image-guided procedures" representing a consistent thread since the early 2000s, with the addition of "modeling" in 2008, and "robotic interventions" in 2012.

Year (s)	Volume (s)	Conference title
1989 to 1990	1091/1232	Image Capture and Display
1991 to 1994	1444 /1653/1897/2164	Image Capture, Formatting, and Display
1995 to 1999	2431/2707/3031/3335/3658	Image Display
2000	3976	Image Display and Visualization
2001	4319	Visualization, Display, and Image-Guided Procedures
2002 to 2006	4681/5029/5367/5744/6141	Visualization, Image-Guided Procedures, and Display
2007	6509	Visualization and Image-Guided Procedures
2008 to 2011	6918/7261/7625/7964	Visualization, Image-Guided Procedures, and Modeling
2012 to 2022	8316/8671/9036/9415/9786/10135/10576/10951/11315/11598	Image-Guided Procedures, Robotic Interventions, and Modeling

of Medical Imaging conference featuring research in novel imaging technologies for image-guided interventions, including CT and cone-beam CT (CBCT).

3 Major Themes

Over the last 30+ years, the areas of major interest presented at the conference have evolved considerably, with numerous major themes evident in research on image display/visualization, surgical tracking/navigation, surgical robotics, interventional imaging, image registration, and modeling. Some highlights among these major themes are noted in the sections below, also reflected by the topics of keynote lectures and workshops summarized in Table 2.

Table 2 Keynote lectures and workshops associated with the MI104 conference since 2006. Accounts prior to 2006 were not available from the conference record, and workshop contributors (marked "N/A") were not reliably recorded in the available conference programs. See the Acknowledgments section for a partial recognition of contributors.

Year	Session	Title	Speakers
2006	Keynote	Visualization and image-guided procedures in medicine: a retrospective and prospective view	Robb
	Workshop	The open-source software movement: what's in it for you?	N/A
2007	Keynote	New methods for image guidance and visualization for cardiac procedures	McVeigh
	Workshop	Software packages for visualization and image-guided procedures	N/A
2008	Keynote	Robo-surgeon: combining medical imaging and mechanical models to automate surgery	Howe
	Workshop	Modeling for therapy guidance and medical imaging	N/A
2009	Keynote	From medical images to virtual physiological humans	Ayache
2010	Keynote	Respiratory effects in PET/CT imaging: impact on diagnosis, quantitative estimation, and therapy	Kinahan
2011	Keynote	Engineering solutions in the operating room: a surgeon's perspective	Herrell
	Workshop	Toolkits and research interfaces for image-guidance and visualization	N/A
2012	Keynote	Medical robotics and computer-integrated interventional medicine	Taylor
	Workshop	Regulatory changes and new opportunities in medical device development	N/A
2013	Keynote	Patient and process specific imaging and visualization for computer assisted interventions	Navab
	Workshop	The image-guided surgery toolkit (IGSTK): a resource for researchers, entrepreneurs, and educators	N/A
2014	Keynote	Engineering therapeutic processes: from research to commodity	Galloway
	Workshop	Commercialization of medical research	N/A
2015	Keynote	Twenty-five years of error	Fitzpatrick
	Workshop	Novel robots for less invasive surgeries	N/A
2016	Keynote	Robot-assisted tumor resection: palpation, incision, debridement, and adhesive closure	Goldberg
	Workshop	Interventional procedures: emerging technologies and clinical applications	N/A

Table 2 (*Continued*).

Year	Session	Title	Speakers
2017	Keynote	Innovations in surgical technology with oncologic application	Jarnagin
	Workshop	Information management, systems integration, standards, and approval issues for the digital operating room	N/A
2018	Keynote	Review of interventional and point-of-care imaging	Piron
	Workshop	Advances in image-guided procedures: a multi-disciplinary joint forum	N/A
2019	Keynote	Bringing transcranial MR-guided focused ultrasound into focus	Butts-Pauly
	Workshop	The visible human project at its 25th anniversary	N/A
2020	Keynote	Healthcare in need of innovation: (exponential) technology and biomedical entrepreneurship as solution providers	Friebe
	Workshop	Advances in image-guided, data-driven interventions	N/A
2021	Keynote	Development of integrated patient-specific models of the mitral valve and left ventricle	Sacks
2022	Keynote	From tool to assistant: towards developing adaptive surgical robots for the operating room	Majewicz-Fey
	Workshop	Careers at the intersection of physics, medical imaging, engineering, and medical physics: SPIE and AAPM perspectives	N/A

Major themes are also clearly evident in review of the conference proceedings. Figure 1 shows such themes in the form of a word cloud drawn from the titles of the 50 most downloaded papers, and Figs. 2–7 highlight some of the figures drawn from work therein. The top 50 most downloaded proceedings papers are given in Table 3, and Table 4 shows the most downloaded proceedings paper each year. The excellence of research presented at the meeting, especially by students and early career scientists, is evident in Table 5, which lists award-winning papers recognized in this conference over the years.

Fig. 1 Word cloud representation of most common terms in the titles from the top 50 most downloaded papers from the conference.

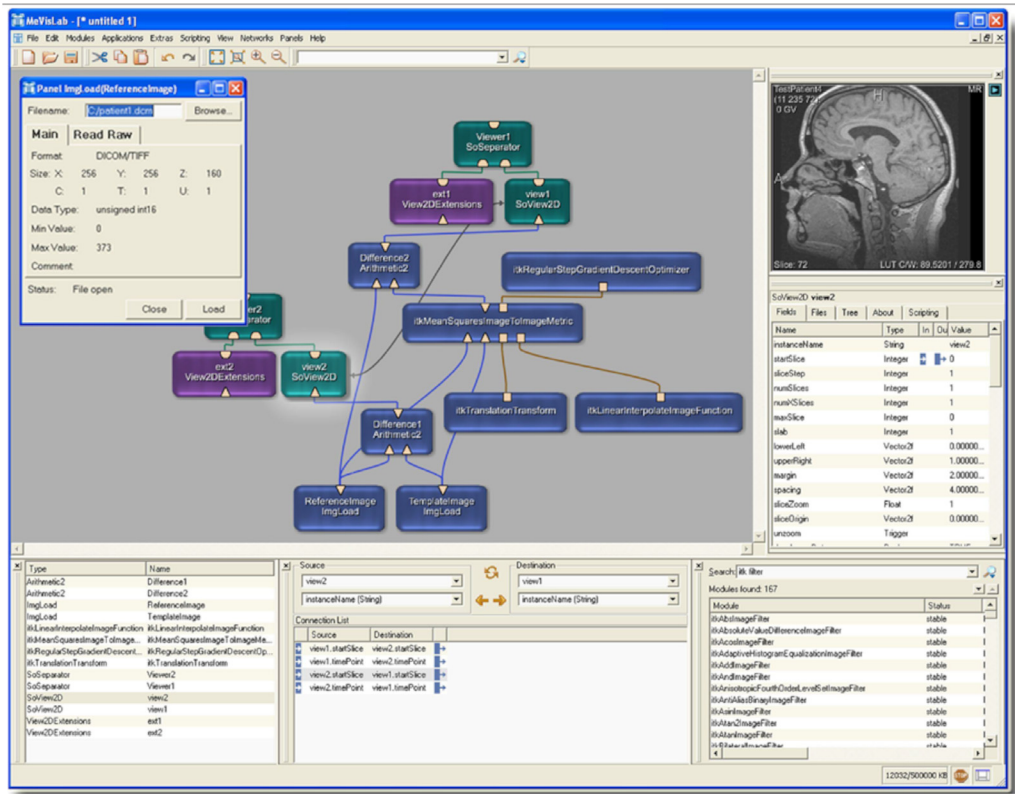

Fig. 2 With its roots in medical image display and visualization, the MI104 conference has been home to research on new software toolkits, such as VTK, ITK, image-guided surgery toolkit (IGSTK), and MITK. Among the top 50 most downloaded proceedings papers (Table 2) is work illustrated by Koenig et al.[1] on the MeVisLab platform that combines modules for image processing, registration, and visualization.

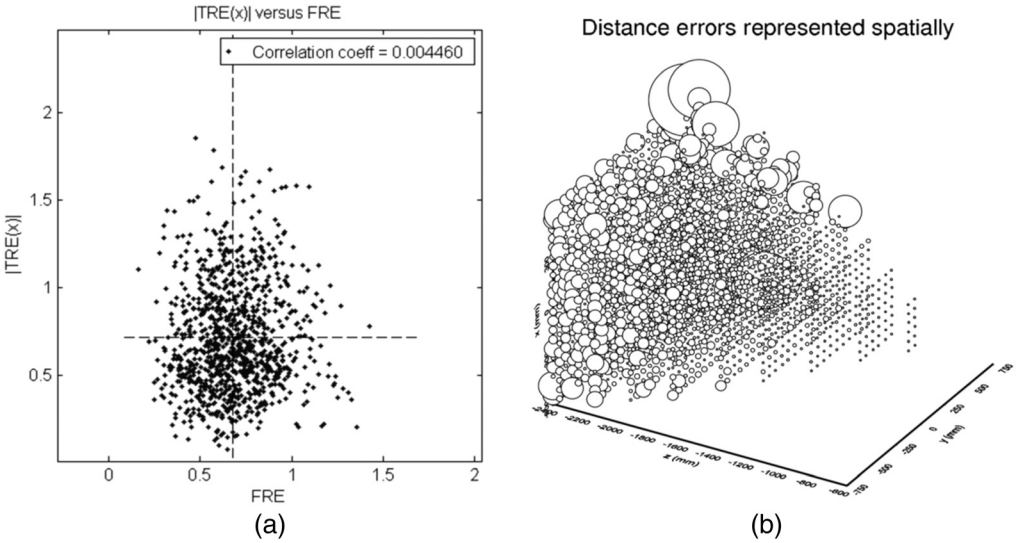

Fig. 3 Surgical tracking and navigation represent important areas of research and technology development for image-guided surgery. Among the top 50 most downloaded proceedings (Table 3) is work illustrated here by (a) West et al.[2] on statistical analysis of FLE, FRE, and TRE and by (b) Wiles et al.[3] on the accuracy of optical and electromagnetic tracking systems.

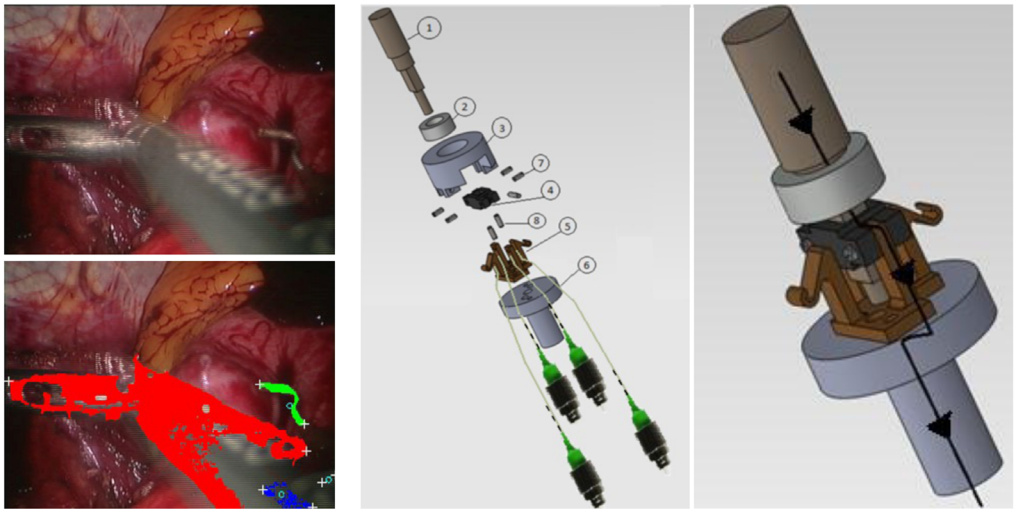

Fig. 4 Surgical robotics have marked a major area of innovation in the last 20 years and are sure to be an even more vibrant area of research in years ahead. Among the top 50 most downloaded proceedings (Table 3) is work illustrated here by (a) Speidel et al.[4] on visual tracking of the da Vinci robot end effectors and by (b) Monfaredi et al.[5] on MR-compatible robot for prostate interventions.

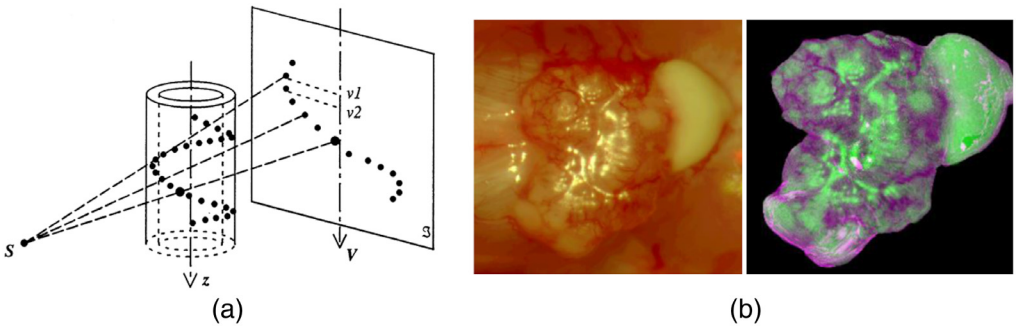

Fig. 5 Research on interventional imaging presented at the conference spans the spectrum of medical imaging modalities. Among the top 50 most downloaded proceedings (Table 3) is work illustrated here by (a) Rougee et al.[6] on geometric calibration of cone-beam CT systems and by (b) Lu et al.[7] on hyperspectral imaging of tumor resection margins.

3.1 *Image Display and Visualization*

From the onset of the conference in 1989 and through the end of the 1990s, image capture, formatting, visualization, and display were the primary themes of the conference. Several notable works include, but are not limited to, the development of image data compression techniques,[12] a first high-performance floating point image computing workstation for medical imaging,[13] presentation of medical images on cathode ray tube (CRT) displays,[14,15] volume rendering of medical images using three-dimensional (3D) texture mapping,[16] and the use of OpenGL in medical imaging,[17] and the characterization of high-resolution liquid crystal displays (LCD) for medical imaging.[18,19]

In concert with image capture and display, several platforms and toolkits were developed to assist with the processing, fusion, and integrated visualization of multi-modality imaging data, such as the 3D VIEWNIX platform,[20] the medical imaging interaction toolkit framework,[21,22] visualization toolkit-Insight toolkit (VTK-ITK) integrated visual programming,[1] and 3D Slicer.[23] Numerous techniques have leveraged such toolkits for integration of 3D data derived from multi-sensor imagery and anatomical atlases using parallel processing, probabilistic quantification, segmentation, and registration for multi-modality medical image fusion.[24,25]

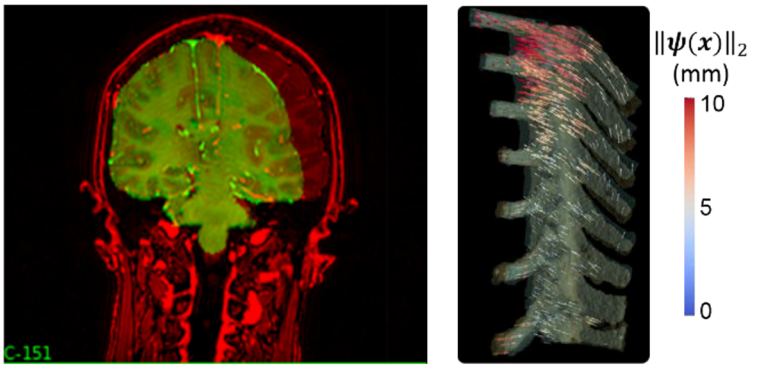

Fig. 6 Rigid and nonrigid registration of multi-modality images is an important aspect of image-guided procedures and has accordingly been among the highlights of the MI104 conference. Among the top 50 most downloaded proceedings (Table 3) is (a) work by Garg et al.[8] on brain shift. Also among such highlights are methods for rigid and nonrigid registration in spine surgery, including (b) work by Reaungamornrat et al.[9] on a Demons registration method based on diffeomorphic transforms with the MIND metric, which won both the Young Scientist Award and the Robert F. Wagner All-Conference Student Paper Award (Table 5).

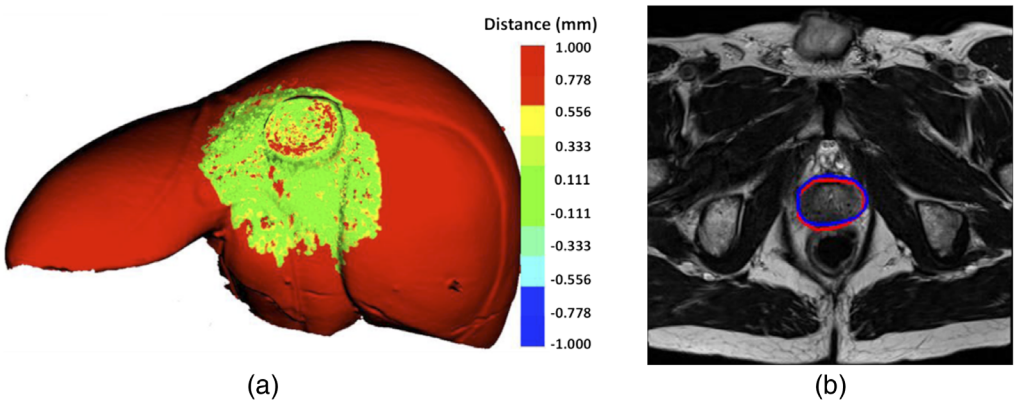

Fig. 7 Physical modeling (and more recently, deep-learning-based modeling) underlies many aspects of image-guided interventions, including tissue properties, image analysis, segmentation, registration, and development of new laboratory and clinical systems. Among the top 50 most downloaded proceedings (Table 3) is (a) work by Röhl et al.[10] on real-time surface reconstruction for laparoscopic surgery and (b) work by Tian et al.[11] on deep-learning-based prostate segmentation.

Throughout the formative years of the conference, advanced image visualization remained an important theme. The development of technologies and techniques to enable multi-modal image manipulation, visualization, and display led to the advent of virtual, augmented and mixed reality applications in medical imaging, with several notable examples being holographic stereograms,[26] real-time auto-stereoscopic visualization,[27] use of stereo and kinetic depth cues for augmented reality of brain imaging,[28] as well as the use of solid models of patient specific anatomy generated from computed tomography/magnetic resonance imaging (CT/MRI) images using laser sintering and laminated object manufacturing techniques.[29]

3.2 *Surgical Tracking/Navigation*

By the turn of the millennium, a spectrum of infrared, videometric, and electromagnetic surgical tracking systems had emerged and found growing application in surgical navigation, primarily in intracranial neurosurgery and spine surgery. Among such systems were the Polaris Spectra (NDI, Mississauga, Ontario, Canada) infrared tracker, the MicronTracker (Claron, Toronto,

Table 3 Top 50 most frequently downloaded papers from the MI104 conference proceedings.

Year	Volume	Authors	Title	DOI	Downloads
2018	10576	Funke et al.	Generative adversarial networks for specular highlight removal in endoscopic images	10.1117/12.2293755	807
2019	10951	Kunz et al.	Metric-based evaluation of fiducial markers for medical procedures	10.1117/12.2511720	533
2011	7964	Kaar et al.	Comparison of two navigation system designs for flexible endoscopes using abdominal 3D ultrasound	10.1117/12.878056	516
2012	8316	Alnowami et al.	A quantitative assessment of using the Kinect for Xbox 360 for respiratory surface motion tracking	10.1117/12.911463	499
2017	10135	Oliver-Butler et al.	Concentric agonist-antagonist robots for minimally invasive surgeries	10.1117/12.2255549	460
2011	7964	Rohl et al.	Real-time surface reconstruction from stereo endoscopic images for intraoperative registration	10.1117/12.877662	449
2019	10951	Han et al.	Large-scale evaluation of V-Net for organ segmentation in image guided radiation therapy	10.1117/12.2512318	442
2011	7964	Mirota et al.	High-accuracy 3D image-based registration of endoscopic video to C-arm cone-beam CT for image-guided skull base surgery	10.1117/12.877803	429
2015	9415	Suzani et al.	Deep learning for automatic localization, identification, and segmentation of vertebral bodies in volumetric MR images	10.1117/12.2081542	399
2015	9415	Vannelli et al.	Dynamic heart phantom with functional mitral and aortic valves	10.1117/12.2082277	391
2017	10135	Mehrtash et al.	DeepInfer: open-source deep learning deployment toolkit for image-guided therapy	10.1117/12.2256011	379
2012	8316	Song et al.	Development and preliminary evaluation of an ultrasonic motor actuated needle guide for 3T MRI-guided transperineal prostate interventions	10.1117/12.911467	372
2014	9036	McLeod et al.	Motion magnification for endoscopic surgery	10.1117/12.2043997	358
2019	10951	Levine et al.	Automatic vertebrae localization in spine CT: a deep-learning approach for image guidance and surgical data science	10.1117/12.2513915	355
2004	5367	Wiles et al.	Accuracy assessment and interpretation for optical tracking systems	10.1117/12.536128	354
2017	10135	Gibson et al.	Deep residual networks for automatic segmentation of laparoscopic videos of the liver	10.1117/12.2255975	353

Table 3 (*Continued*).

Year	Volume	Authors	Title	DOI	Downloads
2019	10951	Sedghi et al.	Semi-supervised image registration using deep learning	10.1117/12.2513020	352
2010	7625	Garg et al.	Enhancement of subsurface brain shift model accuracy: a preliminary study	10.1117/12.845630	348
2018	10576	Ferguson et al.	Toward image-guided partial nephrectomy with the da Vinci robot: exploring surface acquisition methods for intraoperative re-registration	10.1117/12.2296464	346
2018	10576	Kuzhagaliyev et al.	Augmented reality needle ablation guidance tool for irreversible electroporation in the pancreas	10.1117/12.2293671	344
2019	10951	Vijayan et al.	Automatic trajectory and instrument planning for robot-assisted spine surgery	10.1117/12.2513722	327
2010	7625	Daly et al.	Fusion of intraoperative cone-beam CT and endoscopic video for image-guided procedures	10.1117/12.844212	297
2018	10576	Rae et al.	Neurosurgical burr hole placement using the Microsoft HoloLens	10.1117/12.2293680	296
2009	7261	Fitzpatrick	Fiducial registration error and target registration error are uncorrelated	10.1117/12.813601	295
2017	10135	Tian et al.	Deep convolutional neural network for prostate MR segmentation	10.1117/12.2254621	294
2015	9415	Amanov et al.	Additive manufacturing of patient-specific tubular continuum manipulators	10.1117/12.2081999	291
2010	7625	Schumann et al.	Fast automatic path proposal computation for hepatic needle placement	10.1117/12.844186	287
1993	1897	Rougee et al.	Geometrical calibration for 3D x-ray imaging	10.1117/12.146963	282
2020	11315	Friebe	Healthcare in need of innovation: exponential technology and biomedical entrepreneurship as solution providers (Keynote Paper)	10.1117/12.2556776	280
2012	8316	Wang et al.	The Kinect as an interventional tracking system	10.1117/12.912444	279
2014	9036	Lu et al.	Hyperspectral imaging for cancer surgical margin delineation: registration of hyperspectral and histological images	10.1117/12.2043805	261
2015	9415	Speidel et al.	Image-based tracking of the suturing needle during laparoscopic interventions	10.1117/12.2081920	260
2012	8316	Otte et al.	Feasibility of optical detection of soft tissue deformation during needle insertion	10.1117/12.912538	249
2009	7261	Reichl et al.	Ultrasound goes GPU: real-time simulation using CUDA	10.1117/12.812486	248

Table 3 (*Continued*).

Year	Volume	Authors	Title	DOI	Downloads
2011	7964	Kratchman et al.	Toward robotic needle steering in lung biopsy: a tendon-actuated approach	10.1117/12.878792	243
2014	9036	Speidel et al.	Visual tracking of da Vinci instruments for laparoscopic surgery	10.1117/12.2042483	214
2006	6141	Nafis et al.	Method for estimating dynamic EM tracking accuracy of surgical navigation tools	10.1117/12.653448	210
2016	9786	Parent et al.	3D shape tracking of minimally invasive medical instruments using optical frequency domain reflectometry	10.1117/12.2214998	205
2014	9036	Otake et al.	Piecewise-rigid 2D-3D registration for pose estimation of snake-like manipulator using an intraoperative x-ray projection	10.1117/12.2043242	201
2006	6141	Koenig et al.	Embedding VTK and ITK into a visual programming and rapid prototyping platform	10.1117/12.652102	197
2016	9786	Ghafurian et al.	Fast generation of digitally reconstructed radiograph through an efficient preprocessing of ray attenuation values	10.1117/12.2217756	194
2016	9786	Schoch et al.	Cognitive tools pipeline for assistance of mitral valve surgery	10.1117/12.2216059	193
2013	8671	Monfaredi et al.	Design of a decoupled MRI-compatible force sensor using fiber Bragg grating sensors for robot-assisted prostate interventions	10.1117/12.2008160	173
2016	9786	Bodenstedt et al.	Superpixel-based structure classification for laparoscopic surgery	10.1117/12.2216750	169
2003	5029	Sasada et al.	Stationary grid pattern removal using 2D technique for moiré-free radiographic image display	10.1117/12.479595	168
2013	8671	Pati et al.	Accurate pose estimation using single marker single camera calibration system	10.1117/12.2006776	162
2003	5029	Rajagopalan et al.	Image smoothing with Savitzky–Golay filters	10.1117/12.479596	161
2006	6141	Zhang et al.	Freehand 3D ultrasound calibration using an electromagnetically tracked needle	10.1117/12.654906	161
2020	11315	Rettmann et al.	Assessment of proton beam ablation in myocardial infarct tissue using delayed contrast-enhanced magnetic resonance imaging (Erratum)	10.1117/12.2572836	160
2006	6141	Paquit et al.	Near-infrared imaging and structured light ranging for automatic catheter insertion	10.1117/12.655326	159

Table 4 Top downloaded paper from the MI104 conference proceedings each year.

Year	Volume	Authors	Title	DOI	Downloads
1989	1091	Blume and Fand	Reversible and irreversible image data compression using the S-transform and Lempel–Ziv coding	10.1117/12.976433	37
1990	1232	Gazerro et al.	Restoration of images transmitted through coherent fiber bundles	10.1117/12.18881	76
1991	1444	Mankovich et al.	Solid models for CT/MR image display: accuracy and utility in surgical planning	10.1117/12.45149	39
1991	1444	Chan et al.	Visualization and volumetric compression	10.1117/12.45176	39
1992	1653	Ji et al.	Optimizing the display function of display devices	10.1117/12.59493	52
1993	1897	Rougee et al.	Geometrical calibration for 3D x-ray imaging	10.1117/12.146963	282
1994	2164	Udupa et al.	3DVIEWNIX: an open, transportable multidimensional, multimodality, multiparametric imaging software system	10.1117/12.174042	153
1995	2431	Udupa et al.	Fuzzy connectedness and object definition	10.1117/12.207603	88
1996	2707	Rost	Using OpenGL for imaging	10.1117/12.238478	80
1997	3031	Yamaguchi et al.	Natural color reproduction in the television system for telemedicine	10.1117/12.273926	80
1998	3335	Wang et al.	Multimodality medical image fusion: probabilistic quantification, segmentation, and registration	10.1117/12.312497	84
1999	3658	Van Metter et al.	Enhanced latitude for digital projection radiography	10.1117/12.349459	124
2000	3976	Nyul et al.	Standardizing the MR image intensity scales: making MR intensities have tissue-specific meaning	10.1117/12.383076	102
2001	4319	Kim et al.	Advanced amorphous silicon thin film transistor active-matrix organic light-emitting displays design for medical imaging	10.1117/12.428069	115
2002	4681	Blume et al.	Characterization of high-resolution liquid crystal displays for medical images	10.1117/12.466930	113
2003	5029	Sasada et al.	Stationary grid pattern removal using 2D technique for moiré-free radiographic image display	10.1117/12.479595	168
2004	5367	Wiles et al.	Accuracy assessment and interpretation for optical tracking systems	10.1117/12.536128	354
2005	5744	Shamdasani et al.	Improving the visualization of 3D ultrasound data with 3D filtering	10.1117/12.596641	130
2006	6141	Nafis et al.	Method for estimating dynamic EM tracking accuracy of surgical navigation tools	10.1117/12.653448	210

Table 4 (*Continued*).

Year	Volume	Authors	Title	DOI	Downloads
2007	6509	Kruecker et al.	Fusion of real-time transrectal ultrasound with pre-acquired MRI for multi-modality prostate imaging	10.1117/12.710344	156
2008	6918	Eusemann et al.	Dual energy CT: How to best blend both energies in one fused image?	10.1117/12.773095	145
2009	7261	Fitzpatrick	Fiducial registration error and target registration error are uncorrelated	10.1117/12.813601	295
2010	7625	Garg et al.	Enhancement of subsurface brain shift model accuracy: a preliminary study	10.1117/12.845630	348
2011	7964	Kaar et al.	Comparison of two navigation system designs for flexible endoscopes using abdominal 3D ultrasound	10.1117/12.878056	516
2012	8316	Alnowami et al.	A quantitative assessment of using the Kinect for Xbox 360 for respiratory surface motion tracking	10.1117/12.911463	499
2013	8671	Monfaredi et al.	Design of a decoupled MRI-compatible force sensor using fiber Bragg grating sensors for robot-assisted prostate interventions	10.1117/12.2008160	173
2014	9036	McLeod et al.	Motion magnification for endoscopic surgery	10.1117/12.2043997	358
2015	9415	Suzani et al.	Deep learning for automatic localization, identification, and segmentation of vertebral bodies in volumetric MR images	10.1117/12.2081542	399
2016	9786	Parent et al.	3D shape tracking of minimally invasive medical instruments using optical frequency domain reflectometry	10.1117/12.2214998	205
2017	10135	Oliver-Butler et al.	Concentric agonist-antagonist robots for minimally invasive surgeries	10.1117/12.2255549	460
2018	10576	Funke et al.	Generative adversarial networks for specular highlight removal in endoscopic images	10.1117/12.2293755	807
2019	10951	Kunz et al.	Metric-based evaluation of fiducial markers for medical procedures	10.1117/12.2511720	533
2020	11315	Friebe	Healthcare in need of innovation: exponential technology and biomedical entrepreneurship as solution providers (Keynote Paper)	10.1117/12.2556776	280
2021	11598	Dupuy et al.	2D/3D deep registration for real-time prostate biopsy navigation	10.1117/12.2579874	116

Ontario, Canada) videometric tracker, and the Aurora (NDI) electromagnetic tracker.[30] The Spectra became a fairly prevalent component of clinical navigation systems, including the StealthStation (Medtronic, Minneapolis, Minnesota, United States) and VectorVision (BrainLab, Munich, Germany) systems. The MicronTracker presented interesting possibilities in producing one's own marker configurations (easily printed checkerboard patterns) and in fusing registered image or planning information with the video scene. The Aurora eliminated line-of-sight

Table 5 Notable conference (and all-conference) awards earned by students and early-career scientists since 2014.

Year	Award	Title	Awardee	DOI:
2014	Young Scientist Award	Deformable registration for image-guided spine surgery: preserving rigid body vertebral morphology in free-form transformations	Reaungamornrat, S. Johns Hopkins Univ.	10.1117/12.2043474
	2nd Place, Robert F. Wagner All-Conference Best Student Paper Award	Distinguishing benign confounding treatment changes from residual prostate cancer on MRI following laser ablation	Litjens, G. Univ. Nijmegen Medical Ctr.	10.1117/12.2043819
2015	Young Scientist Award	A MR-TRUS registration method for ultrasound-guided prostate interventions	Yang, X. Emory Univ.	10.1117/12.2077825
2016	Young Scientist Award and 1st Place, Robert F. Wagner All-Conference Best Student Paper Award	MIND Demons for MR-to-CT deformable image registration in image-guided spine surgery	Reaungamornrat, S. Johns Hopkins Univ.	10.1117/12.2208621
2017	Young Scientist Award	Fundamental limits of image registration performance: effects of image noise and resolution in CT-guided interventions	Ketcha, M. D. Johns Hopkins Univ.	10.1117/12.2256025
	2nd Place, Robert F. Wagner All-Conference Best Paper Award	Evaluation of a high-resolution patient-specific model of the electrically stimulated cochlea	Cakir, A. Vanderbilt Univ.	10.1117/12.2256005
2018	Young Scientist Award	Intra-operative 360° 3D transvaginal ultrasound guidance during high-dose-rate interstitial gynecologic brachytherapy needle placement	Rodgers, J. R. Western Univ.	10.1117/12.2292767
2019	Young Scientist Award	LV systolic point-cloud model to quantify accuracy of CT derived regional strain	Manohar, A. Univ. of California, San Diego	10.1117/12.2512635
	Student Paper Award	EpiGuide 2D: visibility assessment of a novel multi-channel out-of-plane needle guide for 2D point-of-care ultrasound	Honigmann, S. Univ. of British Columbia	10.1117/12.2513165
2020	Young Scientist Award	Development of ultrasonography assistance robot for prenatal care	Tsumura, R. Worcester Polytechnic Institute	10.1117/12.2550038
	Student Paper Award	Renal biopsy under augmented reality guidance	Pfefferle M. Univ. of Texas at Dallas	10.1117/12.2550593
	1st Place, Robert F. Wagner All-Conference Best Student Paper Award	Multi-body registration for fracture reduction in orthopaedic trauma surgery	Han, R. Johns Hopkins Univ.	10.1117/12.2549708

Table 5 (*Continued*).

Year	Award	Title	Awardee	DOI:
2021	Young Scientist Award	Optimization of hepatic vasculature segmentation from contrast-enhanced MRI, exploring two 3D UNet modifications and various loss functions	Ivashchenko, O. V. Leiden Univ.	10.1117/12.2574267
	Student Paper Award	On the merits of using angled fiber tips in office-based laser surgery of the vocal folds	Chan, I. A. Worcester Polytechnic Institute	10.1117/12.2580454

constraints and was amenable to tracking flexible probes or endoscopes inside the body. Later embodiments included the Polaris Vicra (NDI) suitable to lower cost and laboratory setups, fusionTrack (Atracsys, Puidoux, Switzerland) for increased geometric precision (e.g., in temporal bone surgery), and even systems originally developed for consumer gaming, such as the Kinect (Microsoft, Seattle, Washington, United States).

Early implementations of such tracking/navigation systems employed point-based registration via colocalization of corresponding "fiducial" points in the tracker (world) and 3D image coordinate frames. The analytical basis for understanding the resulting geometric error in the navigation system was described by Fitzpatrck and West[2,31–34] in terms of the fiducial localization error (FLE), fiducial registration error (FRE), and target registration error (TRE), including the effect of the number and geometric arrangement of fiducial markers. The SPIE Image-Guided Procedures conference was an important forum for the development and communication of this quantitative framework that is now commonly invoked throughout the scientific literature in the development and application of new surgical navigation systems.

3.3 *Surgical Robotics*

Given the extensive focus of the Image-Guided Procedures conference on technology and techniques for minimally invasive intervention, surgical robotics, and robot-assisted interventions became a leading theme. Several pioneering works appeared in the proceedings, including the 2012 volume featuring the design of a decoupled MRI-compatible force sensor using fiber Bragg grating sensors for robot-assisted prostate interventions,[5] a flexure-based wrist for needle-sized surgical robots,[35] exploring surface acquisition methods for intraoperative re-registration toward enabling image-guided partial nephrectomy with the da Vinci robot,[36] automatic trajectory and instrument planning for robot-assisted spine surgery,[37] a tendon-actuated approach for robot-enabled needle steering in lung biopsy,[38] or the development of concentric agonist-antagonist robots for minimally invasive surgeries,[39] to name a few.

3.4 *Interventional Imaging*

The MI104 conference has provided a valuable forum for development and clinical application of new interventional imaging technologies across the full spectrum of modalities. Among the most prevalent of these is endoscopy, including laparoscopic, endonasal, thoracic, arthroscopic, bronchoscopic, and neuroendoscopic techniques. Especially in relation to computer vision methods for image processing, feature recognition, 3D reconstruction, and registration to other imaging and planning data, advanced methods for endoscopic video guidance have formed an important means to enhance visualization of the interventional scene.[40] Such work also aims to extend endoscopic capability by integration with robotic assistance, including the da Vinci stereoscopic system[36] as well as a number of emerging robotic systems that could provide a useful platform for controlled manipulation of the endoscope.

Similarly prevalent in the Image-Guided Procedures conference is research that expands the use of ultrasound for interventional imaging. Moreover, the conference has held several joint

symposia and workshops with the ultrasound conference in recent years. Integration of ultrasound with surgical tracking systems enables not only inter-modality registration and guidance[41] but also extends the utility of ultrasound in surgery of the liver, spine, or brain. Systems for transrectal ultrasound have been the subject of considerable research, including a novel robotic assistance system for prostate biopsy or brachytherapy guided by MRI and transrectal ultrasound.[42–44]

As detailed elsewhere in this special issue, the Physics of Medical Imaging conference was home to the development and reporting of new medical imaging technologies, including flat-panel detectors for x-ray fluoroscopy and CBCT. After the turn of the millennium, such technology began to find prevalent use in image-guided radiation therapy, image-guided surgery, and interventional radiology, and the Image-Guided Procedures conference provided an important forum for development, integration, and application of such systems, including first clinical application in areas, such as otolaryngology–head and neck surgery[45] and registration of intraoperative imaging with preoperative CT and MRI.[46]

Among the exciting research programs in image-guided interventions over the last 20 years was the AMIGO operating room[47] constructed at the Brigham & Women's Hospital (Boston, Massachusetts, United States) as a clinical research development and proving ground for the use of multi-modality image guidance. The AMIGO comprised surgical navigation, endoscopy, ultrasound, fluoroscopy, CT, and MR imaging (and later CT-positron emission tomography) within a single operating room (OR) to investigate new clinical applications and the potential advantages of increased precision afforded by such technologies. The research environment facilitated numerous projects reported at the conference and helped to refine the vision for the OR of the Future.

3.5 *Image Registration: Rigid, Deformable, and Inter-Modality Registration Techniques*

Just as image registration is integral to the practice of image-guided interventions, so has it been among the outstanding science presented at the conference. Point-based registration approaches (and the analytical models describing registration error) are mentioned above in relation to surgical tracking/navigation.[2,3,31–34]

Numerous methods and applications of image-based 3D-2D registration (alternatively 2D-3D registration, making no claim as to the order or which constitutes the moving or fixed image) have been reported at the MI104 conference, with the term broadly applied to video-to-volume registration (e.g., endoscopy to CT), slice-to-volume registration (e.g., ultrasound to MRI), and projection-to-volume registration (e.g., fluoroscopy to CT).[48–57] Such work includes novel methods and implementations for 3D-2D registration with applications ranging from needle interventions to catheter guidance and orthopedic surgery. Prominent among these are methods for registration of 3D CT (or CBCT) to intraoperative 2D fluoroscopy, with many groups reporting research on novel objective functions, motion models (including piecewise rigid registration), and optimization methods.[55] Such work has helped CT-to-fluoroscopy registration emerge within the modern standard of surgical image guidance. Ongoing research seeks to accurately register MRI with fluoroscopy and improve robustness and runtime via deep-learning approaches.

Similarly, 3D-3D image registration, including inter- and intra-modality images and rigid and nonrigid motion models, presents a major area of research in image-guided interventions, with healthy overlap and shared interest with the Image Processing conference.[8,9,58–66] Research in 3D-3D image registration has focused primarily on challenges associated with inter-modality registration (CT, MRI, and ultrasound) and nonrigid registration models. Methods to handle nonlinearly related image intensities in inter-modality registration primarily focus on novel objective functions, e.g., the modality-insensitive neighborhood descriptor (MIND), and more recently, learned relationships between inter-modality image appearance via CNNs and generative adversarial networks. Research employing nonrigid motion models, e.g., B-spline, Demons, etc., has sought to bring such capability to applications in image-guided surgery, especially in the context of highly deformable tissues, such as the brain, lungs, and liver. Here again, deep-learning architectures represent an emerging theme that extends previous research based on physics-based, diffeomorphic motion models.

3.6 *Modeling for Image-Guided Interventions*

In concert with the advances in image computing, manipulation, visualization, and display in the effort to support image-guided interventions, modeling became an integral component in preoperative treatment planning. One such example is the first assessment of the display accuracy and clinical utility of virtual and solid models of patient anatomy generated from CT/MRI imaging data using rapid prototyping techniques,[29] as well as the use of constitutive modeling for the development of a brain phantom.[67] Several modeling tools have been used in conjunction with image processing techniques toward improving segmentations, such as statistical multi-vertebrae shape and pose model for segmentation of CT images,[68] or registration for applications, such as brain shift estimation and correction, e.g., enhancement of subsurface brain shift model accuracy.[69]

Although at first modeling methods were solely focused on the generation of faithful geometric representations of patient specific anatomy from medical images, modeling soon evolved to encompass the integration of functional data (i.e., electrophysiology) and its mapping onto image-derived patient specific morphology.[69] Furthermore, several theoretical modeling approaches have been used to estimate organ motion when such motion could not be easily measured, such as modeling liver motion and deformation during the respiratory cycle using intensity-based free-form registration of gated MR images,[70] or estimate an organs specific response to therapy[71,72] as a means to predict and optimize treatment outcome. Similarly, other modeling applications include automated detection of specific workflow stages, such as recognition of risk situations based on endoscopic instrument tracking and knowledge-based situation modeling[73] or specific feature detection, e.g., mitotic cell recognition using hidden Markov models.[74]

4 Notable Papers and Awards

The MI104 conference proceedings have provided a valuable forum for the publication of groundbreaking work, documenting content presented in oral and poster presentations, often including late-breaking results appearing only in the SPIE Proceedings or preliminary to eventual peer-review journal publications. The conference also formed the basis for special sections in the *Journal of Medical Imaging* on "Image Guidance Technology Platforms" in 2018[75] and "Interventional Data Science" in 2020.[76]

The top 50 most downloaded papers from the MI104 conference proceedings are summarized in Table 3, with a relatively recent (2018) paper on deep-learning-based image corrections earning the top spot (>800 downloads). Table 4 shows the top downloaded paper each year, with keywords from the titles of these papers pictorially shown in Fig. 1. These papers also demonstrate the importance of the meeting as a forum for student researchers to present their work, with a majority of the papers noted in Tables 3 and 4 having a graduate student as first author.

In recent years, the conference program committee has recognized outstanding papers by early-career scientists via the Young Scientist Award (sponsored by Siemens Healthineers, Princeton, New Jersey, United States), the Best Student Paper Award (sponsored by Intuitive Surgical, Sunnyvale, California, United States), and Best Poster Awards (sponsored by NDI Northern Digital Inc., Waterloo, Ontario, Canada). Student papers are also eligible for the symposium-wide Robert F. Wagner (and previously Michael B. Merickel) *Best Student Paper Award*. Table 5 summarizes such recognitions earned by papers in the Image-Guided Procedures, Robotic Interventions and Modeling conference since 2014, when reliable records regarding awards were first available.

5 Conclusions and Outlook: An Important Forum for Advancing Interventional Medicine

As SPIE celebrates the 50th anniversary of the Medical Imaging Symposium, we also celebrate nearly 35 years of the MI104 conference, growing from its roots in the conference on Image Capture and Display and now termed the conference on Image-Guided Procedures, Robotic Interventions, and Modeling.

The increasing prevalence of minimally invasive interventional radiology and surgical approaches over the last 20 years has been driven by the need for safer, more precise, and effective therapies, and the emergence of such therapies has been enabled in large part by the technologies that were featured for the first time during their development via this conference. MI104 has provided a valuable forum and ongoing dialog regarding research and translation of technologies for surgical navigation, advanced visualization, intraoperative imaging, robotic assistance, and modeling of tissues, devices, and therapeutic response. Such technologies have been integral to advances in patient care, and their continued adoption will continue to require close partnerships among clinicians and engineers, including academics and industry. The years ahead are sure to bring further technology advances, studies to demonstrate the benefits in outcomes, and recognition of costs and value-based care.

The MI104 conference on Image-Guided Procedures, Robotic Interventions, and Modeling will continue to provide a valuable forum for research that enables and expands the widespread use of minimally invasive interventions, including but not limited to devising more accurate surgical target localization, precise and accurate registration of multiple data sources and systems, and novel advances in the surgical armamentarium. New paradigms for multi-modality imaging accompanied by intuitive and workflow-compatible visualization will surely advance, and new devices and tools that minimize technology footprint in the interventional suite to facilitate clinical adoption and mitigate cost and resistance to change will be equally important. The continuing theme of open science and open source data and computational tools is anticipated to grow to facilitate even broader engagement and participation in such advances throughout the scientific community.

Numerous additional areas of major challenge loom on the horizon. First are the challenges presented by clinical needs and the engineering of new technologies to meet those needs. These challenges, brought to light by the informed insight of clinical collaboration, have been and will continue to be a driving force for cutting-edge research presented at the meeting.

Second are challenges of a logistical and/or financial nature, recognizing the need for improved workflow, integration, and interoperability among technologies entering the circle of care as well as the need to recognize and mitigate cost and to demonstrate clear evidence of improved quality, outcomes, and value. An important emerging theme is the development of frugal image-guided surgical and interventional systems that are suitable to resource-constrained healthcare centers and remote clinical centers. Such challenges loom in developed, underdeveloped, and developed countries alike, and there is tremendous opportunity to advance healthcare in such contexts. The community of researchers who regard MI104 as a home for their work in image-guided procedures, robotic assistance, modeling, and data-driven procedural guidance are well positioned to participate in this trend.

Third are challenges of a social-scientific nature in the rapidly changing landscape and format of scientific conferences following the pandemic of 2020. At the time of writing, many of us remember SPIE Medical Imaging 2020 as the last in-person meeting attended in-person prior to the pandemic. The Medical Imaging 2021 symposium was held entirely online, and SPIE Medical Imaging 2022 marked a return to an in-person symposium. Given the acceleration and evolution in modes of scientific communication in recent years, we anticipate an ongoing evolution in meeting format that will synergize the efficiencies of digital interaction with the vibrancy of personal interaction that has marked the last 50 years of the symposium.

Disclosures

JHS discloses sponsored research and licensing agreements with Siemens Healthineers (Forchheim Germany), Carestream Health (Rochester USA), Medtronic (Minneapolis USA), and Elekta Oncology (Stockholm Sweden).

Acknowledgments

People Behind the MI104 Conference: The scientists participating in the conference represent the cutting edge of what has become one of the premier gatherings for scientific research in

medical imaging. No review of its success would be complete, however, without acknowledging the organizers at SPIE who have contributed their time and expertise to its growth and ongoing success. Among these are Sandy Hoelterhoff, Robbine Waters, Lillian Dickinson, Kirsten Anderson, and Matt Novak (Conference Program Coordinators), Diane Cline and Marilyn Gorsuch (SPIE Event Managers), Maryellen Giger (SPIE Past President, SPIE Medical Imaging Past Symposium Chair, and SPIE *Journal of Medical Imaging* Editor-in-Chief), as well as the numerous Symposium Chairs and MI104 Conference Chairs, whose contributions behind the scenes have been paramount to make the annual conference a success and its proceedings a valuable contribution to the scientific literature. While the available conference records did not reliably capture the names of workshop contributors summarized in Table 2, within the authors' memory are the following individuals gratefully acknowledged for their valuable contributions (with apologies for unintended omissions): Dr. Michael Ackermann, Dr. Kevin Cleary, Dr. Christian Eusemann, Dr. Maryellen Giger, Dr. Pierre Jannin, Dr. Despina Kontos, Dr. Michael Miga, Dr. Nobuhiko Hata, Dr. David R. Holmes III, Brandon Nelson, Dr. Guy Shechter, Dr. Jonathan Sorger, Dr. Robert Webster III, Dr. Kenneth Wong, and Dr. Terry Yoo. Finally, the continuous and generous sponsorship of several organizations have supported the continued excellence of the conference and recognition of outstanding work by students and early-career scientists. Among these are Siemens Healthineers (Young Scientist Award), Intuitive Surgical (Student Paper Award), Northern Digital Inc. (NDI poster awards), as well as sponsorship from SPIE in support of the symposium-wide Michael B. Merickel and Robert F. Wagner All-Conference Best Student Paper Awards.

References

1. M. Koenig et al., "Embedding VTK and ITK into a visual programming and rapid prototyping platform," *Proc. SPIE* **6141**, 61412O (2006).
2. J. B. West, J. M. Fitzpatrick, and P. G. Batchelor, "Point-based registration under a similarity transform," *Proc. SPIE* **4322**, 611–622 (2001).
3. A. D. Wiles, D. G. Thompson, and D. D. Frantz, "Accuracy assessment and interpretation for optical tracking systems," *Proc. SPIE* **5367**, 421–432 (2004).
4. S. Speidel et al., "Visual tracking of da Vinci instruments for laparoscopic surgery," *Proc. SPIE* **9036**, 903608 (2014).
5. R. Monfaredi et al., "Design of a decoupled MRI-compatible force sensor using fiber Bragg grating sensors for robot-assisted prostate interventions," *Proc. SPIE* **8671**, 867118 (2013).
6. A. Rougee et al., "Geometrical calibration for 3D x-ray imaging," *Proc. SPIE* **1897** 161–169 (1993).
7. G. Lu et al., "Hyperspectral imaging for cancer surgical margin delineation: registration of hyperspectral and histological images," *Proc. SPIE* **9036**, 90360S (2014).
8. I. Garg et al., "Enhancement of subsurface brain shift model accuracy: a preliminary study," *Proc. SPIE* **7625**, 76250J (2010).
9. S. Reaungamornrat et al., "MIND Demons for MR-to-CT deformable image registration in image-guided spine surgery," *Proc. SPIE* **9786**, 97860H (2016).
10. S. Röhl et al., "Real-time surface reconstruction from stereo endoscopic images for intraoperative registration," *Proc. SPIE* **7964**, 796414 (2011).
11. Z. Tian, L. Liu, and B. Fei, "Deep convolutional neural network for prostate MR segmentation," *Proc. SPIE* **10135**, 101351L (2017).
12. H. Blume and A. Fand, "Reversible and irreversible image data compression using the S-transform and Lempel–Ziv coding," *Proc. SPIE* **1091**, 2–18 (1989).
13. K. S. Mills et al., "High-performance floating-point image computing workstation for medical applications," *Proc. SPIE* **1232**, 246–256 (1990).
14. H. R. Blume et al., "Comparison of the physical performance of high-resolution CRT displays and films recorded by laser image printers and displayed on light-boxes and the need for a display standard," *Proc. SPIE* **1232**, 1–18 (1990).
15. E. Muka, H. R. Blume, and S. J. Daly "Display of medical images on CRT soft-copy displays: a tutorial," *Proc. SPIE* **2431**, 341–359 (1995).

16. S.-Y. Guan and R. G. Lipes, "Innovative volume rendering using 3D texture mapping," *Proc. SPIE* **2164**, 382–392 (1994).
17. R. J. Rost, "Using OpenGL for imaging," *Proc. SPIE* **2707**, 473–484 (1996).
18. H. R. Blume et al., "Characterization of high-resolution liquid crystal displays for medical images," *Proc. SPIE* **4681**, 271–292 (2002).
19. H. R. Blume et al., "Characterization of liquid-crystal displays for medical images: II," *Proc. SPIE* **5029**, 449–473 (2003).
20. J. K. Udupa et al., "3DVIEWNIX: an open, transportable, multidimensional, multimodality, multiparametric imaging software system," *Proc. SPIE* **2164**, 58–73 (1994).
21. I. Wolf et al., "The medical imaging interaction toolkit (MITK): a toolkit facilitating the creation of interactive software by extending VTK and ITK," *Proc. SPIE* **5367**, 16–27 (2004).
22. I. Wolf et al., "Curved reformations using the medical imaging interaction toolkit (MITK)," *Proc. SPIE* **5744**, 831–838 (2005).
23. S. Pieper, M. Halle, and R. Kikinis, "3D slicer," in *2nd IEEE Int. Symp. Biomed. Imaging: Nano to Macro (IEEE Cat No. 04EX821)*, Vol. 1, pp. 632–635 (2004).
24. Y. J. Wang et al., "Multimodality medical image fusion: probabilistic quantification, segmentation, and registration," *Proc. SPIE* **3335**, 239–249 (1998).
25. A. Uneri et al., "Architecture of a high-performance surgical guidance system based on C-arm cone-beam CT: software platform for technical integration and clinical translation," *Proc. SPIE* **7964**, 796422 (2011).
26. C. F. X. de Mendonca et al., "Fast holographic-like stereogram display using shell rendering and a holographic screen," *Proc. SPIE* **3658**, 1–9 (1999).
27. L. Portoni et al., "Real-time auto-stereoscopic visualization of 3D medical images," *Proc. SPIE* **3976**, 37–44 (2000).
28. C. R. Maurer, Jr. et al., "Augmented-reality visualization of brain structures with stereo and kinetic depth cues: system description and initial evaluation with head phantom," *Proc. SPIE* **4319** 445–456 (2001).
29. N. J. Mankovich et al., "Solid models for CT/MR image display: accuracy and utility in surgical planning," *Proc. SPIE* **1444**, 2–8 (1991).
30. E. Wilson et al., "A hardware and software protocol for the evaluation of electromagnetic tracker accuracy in the clinical environment: a multi-center study," *Proc. SPIE* **6509**, 65092T (2007).
31. A. Danilchenko and J. M. Fitzpatrick, "General approach to error prediction in point registration," *Proc. SPIE* **7625**, 76250F (2010).
32. J. B. West and J. M. Fitzpatrick, "Point-based rigid registration: clinical validation of theory," *Proc. SPIE* **3979**, 353–359 (2000).
33. J. M. Fitzpatrick, J. B. West, and C. R. Maurer Jr., "Derivation of expected registration error for point-based rigid-body registration," *Proc. SPIE* **3338**, 1–12 (1998).
34. J. M. Fitzpatrick, "Fiducial registration error and target registration error are uncorrelated," *Proc. SPIE* **7261**, 726102 (2009).
35. D. P. Losey et al., "A flexure-based wrist for needle-sized surgical robots," *Proc. SPIE* **8671**, 86711G (2013).
36. J. M. Ferguson et al., "Toward image-guided partial nephrectomy with the da Vinci robot: exploring surface acquisition methods for intraoperative re-registration," *Proc. SPIE* **10576**, 1057609 (2018).
37. R. C. Vijayan et al., "Automatic trajectory and instrument planning for robot-assisted spine surgery," *Proc. SPIE* **10951**, 1095102 (2019).
38. L. B. Kratchman et al., "Toward robotic needle steering in lung biopsy: a tendon-actuated approach," *Proc. SPIE* **7964**, 79641I (2011).
39. K. Oliver-Butler, Z. H. Epps, and D. C. Rucker, "Concentric agonist-antagonist robots for minimally invasive surgeries," *Proc. SPIE* **10135**, 1013511 (2017).
40. L. Rai and W. E. Higgins, "Continuous endoscopic guidance via interleaved video tracking and image-video registration," *Proc. SPIE* **6918**, 69182R (2008).
41. R. Walsh et al., "Design of a tracked ultrasound calibration phantom made of LEGO bricks," *Proc. SPIE* **9036**, 90362C (2014).

42. J. Bax et al., "3D transrectal ultrasound prostate biopsy using a mechanical imaging and needle-guidance system," *Proc. SPIE* **6918**, 691825 (2008).
43. H. Xu et al., "Accuracy validation for MRI-guided robotic prostate biopsy," *Proc. SPIE* **7625**, 762517 (2010).
44. S.-E. Song et al., "Development and preliminary evaluation of an ultrasonic motor actuated needle guide for 3T MRI-guided transperineal prostate interventions," *Proc. SPIE* **8316**, 831614 (2012).
45. J. H. Siewerdsen et al., "Cone-beam CT with a flat-panel detector on a mobile C-arm: preclinical investigation in image-guided surgery of the head and neck," *Proc. SPIE* **5744**, 789–797 (2005).
46. S. Nithiananthan et al., "Demons deformable registration for cone-beam CT guidance: registration of pre- and intra-operative images," *Proc. SPIE* **7625**, 76250L (2010).
47. S.-E. Song et al., "Workflow assessment of 3T MRI-guided transperineal targeted prostate biopsy using a robotic needle guidance," *Proc. SPIE* **9036**, 903612 (2014).
48. H. Imamura et al., "Registration of preoperative CTA and intraoperative fluoroscopic image sequence for assisting endovascular stent grafting," *Proc. SPIE* **4681**, 500–509 (2002).
49. J. P. Helferty et al., "CT-video registration accuracy for virtual guidance of bronchoscopy," *Proc. SPIE* **5369**, 150–164 (2004).
50. H. Hong, K. Kim, and S. Park, "Fast 2D-3D marker-based registration of CT and x-ray fluoroscopy images for image-guided surgery," *Proc. SPIE* **6141**, 61412G (2006).
51. H. Sundar et al., "A novel 2D-3D registration algorithm for aligning fluoro images with 3D pre-op CT/MR images," *Proc. SPIE* **6141**, 61412K (2006).
52. J. Hummel et al., "Endoscopic navigation system using 2D/3D registration," *Proc. SPIE* **6141**, 614114 (2006).
53. X. Huang et al., "Intra-cardiac 2D US to 3D CT image registration," *Proc. SPIE* **6509**, 65092E (2007).
54. R. H. Gong and P. Abolmaesumi, "2D/3D registration with the CMA-ES method," *Proc. SPIE* **6918**, 69181M (2008).
55. S. Pawiro et al., "A new gold-standard dataset for 2D/3D image registration evaluation," *Proc. SPIE* **7625**, 76251V (2010).
56. P. Steininger et al., "A novel class of machine-learning-driven real-time 2D/3D tracking methods: texture model registration (TMR)," *Proc. SPIE* **7964**, 79640G (2011).
57. Y. Otake et al., "Automatic localization of target vertebrae in spine surgery using fast CT-to-fluoroscopy (3D-2D) image registration," *Proc. SPIE* **8316**, 83160N (2012).
58. J. G. Verly et al., "Nonrigid registration and multimodality fusion for 3D image-guided neurosurgical planning and navigation," *Proc. SPIE* **5367**, 735–746 (2004).
59. T. Guo, Y. P. Starreveld, and T. M. Peters, "Evaluation and validation methods for inter-subject nonrigid 3D image registration of the human brain," *Proc. SPIE* **5744**, 594–603 (2005).
60. S. Tang et al., "Application of nonrigid registration in ablation of liver cancer," *Proc. SPIE* **6509**, 650931 (2007).
61. M. Ferrant et al., "Real-time simulation and visualization of volumetric brain deformation for image-guided neurosurgery," *Proc. SPIE* **4319**, 366–373 (2001).
62. B. K. Lamprich and M. I. Miga, "Analysis of model-updated MR images to correct for brain deformation due to tissue retraction," *Proc. SPIE* **5029**, 552–560 (2003).
63. J. M. Blackall et al., "Tracking alignment of sparse ultrasound with preoperative images of the liver and an interventional plan using models of respiratory motion and deformation," *Proc. SPIE* **5367**, 218–227 (2004).
64. A. Al-Mayah et al., "Effect of heterogeneous material of the lung on deformable image registration," *Proc. SPIE* **7261**, 72610V (2009).
65. X. Fan et al., "Graphical user interfaces for simulation of brain deformation in image-guided neurosurgery," *Proc. SPIE* **7625**, 762535 (2010).
66. R. Han et al., "Deformable MR-CT image registration using an unsupervised synthesis and registration network for neuro-endoscopic surgery," *Proc. SPIE* **11598**, 1159819 (2021).
67. A. Puzrin et al. "Image guided constitutive modeling of the silicone brain phantom," *Proc. SPIE* **5744**, 157–164 (2005).

68. A. Rasoulian, R. N. Rohling, and P. Abolmaesumi, "A statistical multi-vertebrae shape+pose model for segmentation of CT images," *Proc. SPIE* **8671**, 86710P (2013).
69. Q. Zhang, R. Eagleson, and T. M. Peters, "Graphics hardware based volumetric medical dataset visualization and classification," *Proc. SPIE* **6141**, 61412T (2006).
70. C. Villard et al., "Toward realistic radiofrequency ablation of hepatic tumors 3D simulation and planning," *Proc. SPIE* **5367**, 586–595 (2004).
71. C. A. Linte et al., "Image-based modeling and characterization of RF ablation lesions in cardiac arrhythmia therapy," *Proc. SPIE* **8671**, 86710E (2013).
72. M. E. Rettmann et al., "Segmentation of left atrial intracardiac ultrasound images for image guided cardiac ablation therapy," *Proc. SPIE* **8671**, 86712D (2013).
73. S. Speidel et al., "Recognition of risk situations based on endoscopic instrument tracking and knowledge based situation modeling," *Proc. SPIE* **6918**, 69180X (2008).
74. G. M. Gallardo et al., "Mitotic cell recognition with hidden Markov models," *Proc. SPIE* **5367**, 661–668 (2004).
75. A. Simpson and M. Miga, "Special section guest editorial: Technology platforms for treatment and discovery in human systems: novel work in image-guided procedures, robotic interventions, and modeling," *J. Med. Imaging* **5**(2), 021201 (2018).
76. A. L. Simpson and M. I. Miga, "Special section guest editorial: interventional and surgical data science for data-driven patient outcomes," *J. Med. Imaging* **7**(3), 031501 (2020).

Jeffrey H. Siewerdsen received his PhD in physics from the University of Michigan (Ann Arbor, Michigan) in 1998, where he worked on the early development of flat-panel x-ray detectors. At William Beaumont Hospital (Royal Oak, Michigan, 1998–2002), he was on the team that developed the first systems for CBCT-guided radiation therapy. At the Ontario Cancer Institute and University of Toronto (2002–2009), his research involved intraoperative 3D imaging and registration. At Johns Hopkins University (2009–2022), he is the John C. Malone Professor and vice-chair in Biomedical Engineering and founding co-director of the Carnegie Center for Surgical Innovation and the I-STAR Labs. In 2022, he joined the MD Anderson Cancer Center as faculty and director of surgical data science.

Cristian A. Linte is an associate professor in Biomedical Engineering and Center for Imaging Science at Rochester Institute of Technology. His research focuses on the development, implementation, and evaluation of biomedical image computing, visualization, and navigation tools in support of computer-assisted diagnosis and therapy. He has been attending and disseminating his research at SPIE Medical Imaging since 2006, has been on the program committee of the Image-Guided Procedures, Robotic Interventions, and Modeling conference since 2014, and has served as chair of this conference during 2019–2023.