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Design of a Robotic HIFU System for Battlefield Trauma Care

Jason Wheeler   Stephen P. Buerger
Sandia National Laboratories, Albuquerque, NM

Ralf Seip   Narendra T. Sanghvi
Focus Surgery, Inc., Indianapolis, IN

Ron Marchessault
Telemedicine and Advanced Technology Research Center, Army Medical Research and Materiel Command, Fort Detrick, MD

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

Project Overview

- Goal: Develop a remotely operable, high-intensity focused ultrasound (HIFU) based system for cauterizing ruptured blood vessels in critically-wounded soldiers
  - Compatible with LSTAT / CSTAT platform
    - LSTAT: Life Support for Trauma and Transport
    - CSTAT: Critical Systems for Trauma and Transport
  - Step toward Autonomous Combat Casualty Care

- STTR – US Army Medical Research and Materiel Command
  - Phase 1 (design) completed, phase 2 (prototype) underway

- Team:
  - Focus Surgery, Inc. - HIFU
  - Sandia National Laboratories - Robotics
  - XDATA Corporation – Software integration

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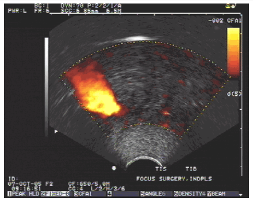
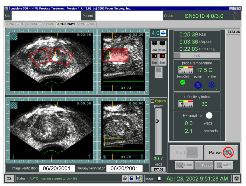
System Elements and Operation

Operator Interface

- Doppler/ ultrasound/ cameras



- Treatment planning / monitoring

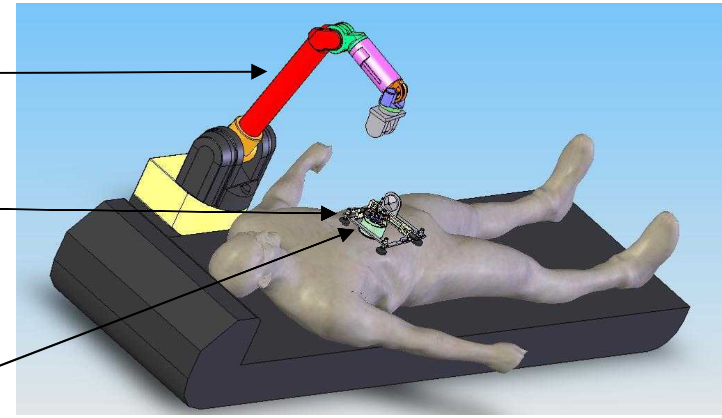


- Robot guidance

RF

Local Control

- Robot arm
- Laptop PC
- End-effector
- Cameras, LSTAT, hardware
- HIFU / imaging



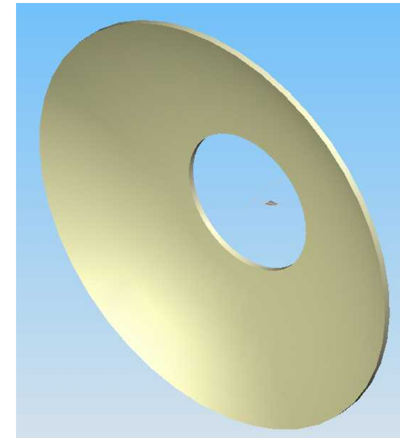
- **Remote operator provides high-level commands, makes decisions about treatment**
- **Local system semi-autonomously executes lower-level operations**
- **Treatment concept:**
  - **Robot places end-effector module in gross area of injury**
  - **Doppler / ultrasound scan of area locates laceration flow**
  - **Operator provides treatment path, timecourse**
  - **HIFU applicator & end-effector execute treatment**
  - **Scan & repeat as needed**
  - **Robot retrieves module**

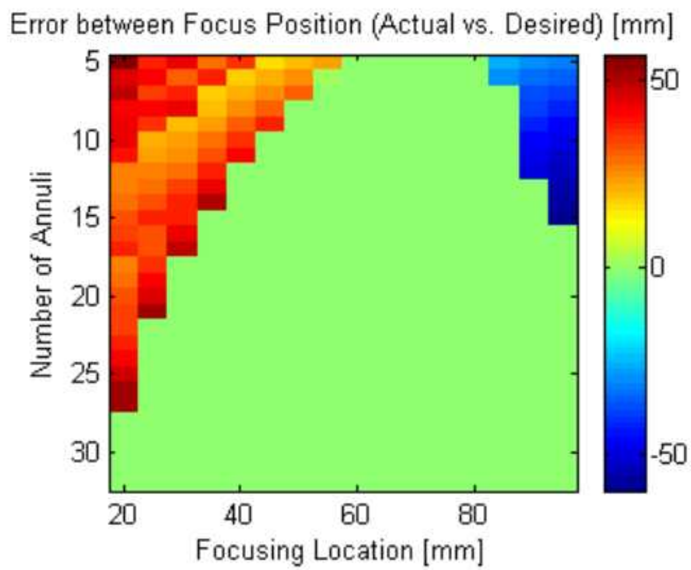
HIFU Design

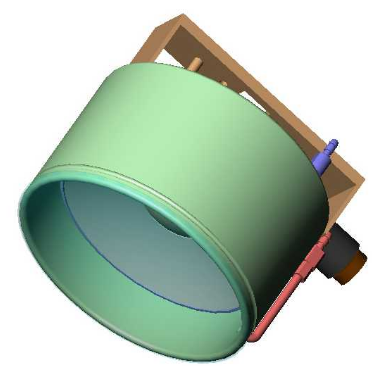
- **Design constraints**
  - **1000 W/cm^2 min intensity at tissue depths from skin surface to 7 cm**
  - **10 W/cm^2 max intensity at crystal surface**

Aperture	74 mm
Radius of Curvature	74 mm
Operating Frequency	2.2 MHz
Center Hole Opening	25 mm diam.
Number of Annuli	23 (Equal Area)
Focusing Range	30 to 95 mm (0 to 75 mm)
Recess of Array in Housing	20 mm

- **Variables**
  - **Aperture**
  - **Radius of Curvature**
  - **Operating Frequency**
  - **Center Hole Opening**
  - **Number of Annuli**







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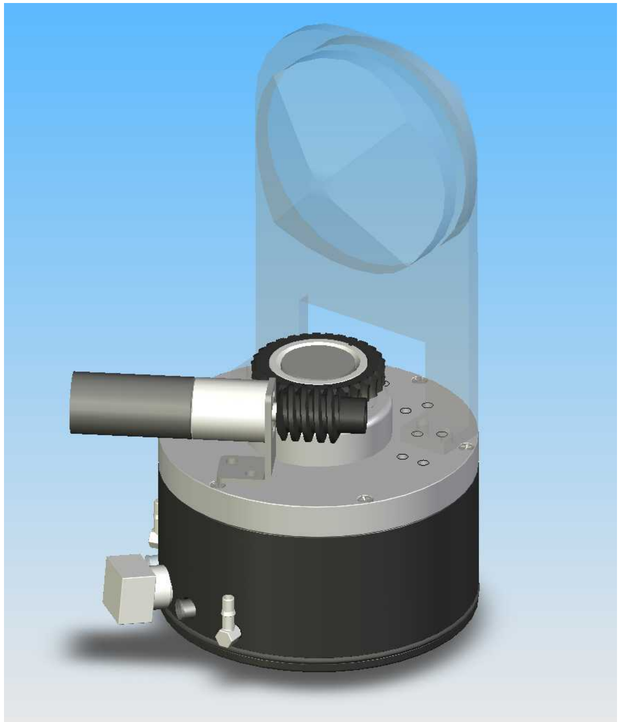
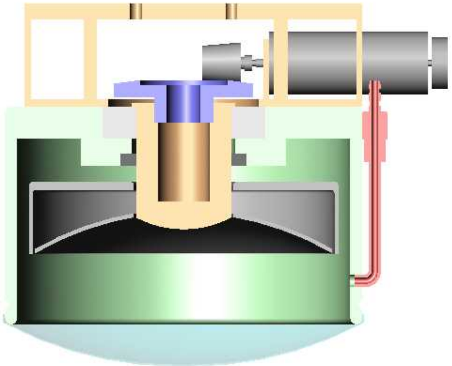
Applicator

- Cylinder (approx. 75 mm diameter) houses HIFU array and commercial imaging array
- Drive system provides 180º stepwise rotation for imaging
  - 3D images are assembled from 2D slices
  - No rotation during treatment
- Filled with chilled, degassed water; flexible, transparent bolus permits adjustable standoff from skin
- Attaches to end-effector, or moved directly by robot arm for limb treatment





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Robotic Considerations

- Close physical contact with humans represents significant paradigm shift from traditional robotics, presents substantial technical challenges
  - Pedestal robots are good at moving in free space, bad at applying forces to stiff objects
    - This application requires modest force applied between applicator and skin, even with some relative movement
  - Substantive interaction with static / dynamic objects makes stability much more difficult to guarantee
  - Close contact with humans also makes *consequences* of instability severe

- Two solutions used for this system:
  - Backdriveability: Robots that "get out of way" when pushed can be made to safely control interaction
  - Modularity: Removes human interaction tasks from strong, complex robot and shift this job to simple mechanical elements

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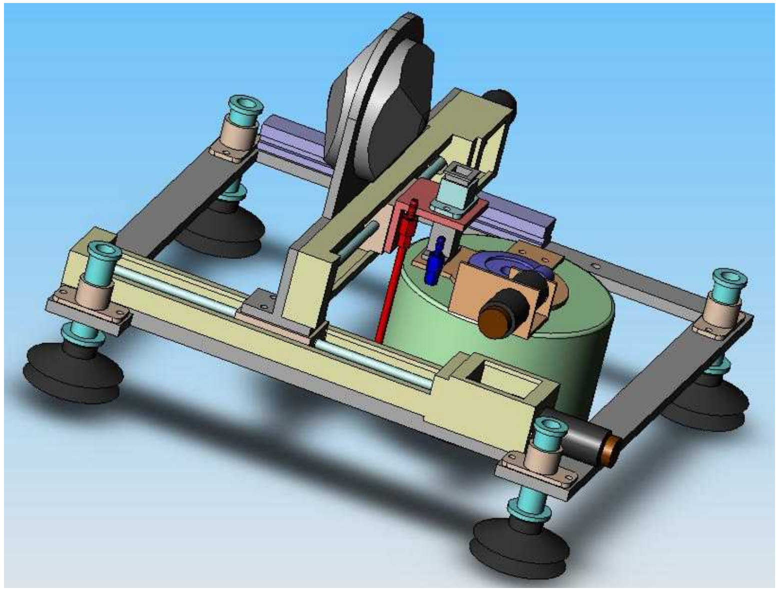
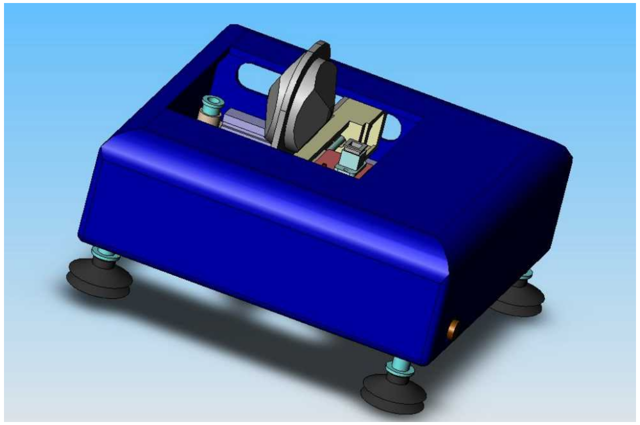
End-Effector

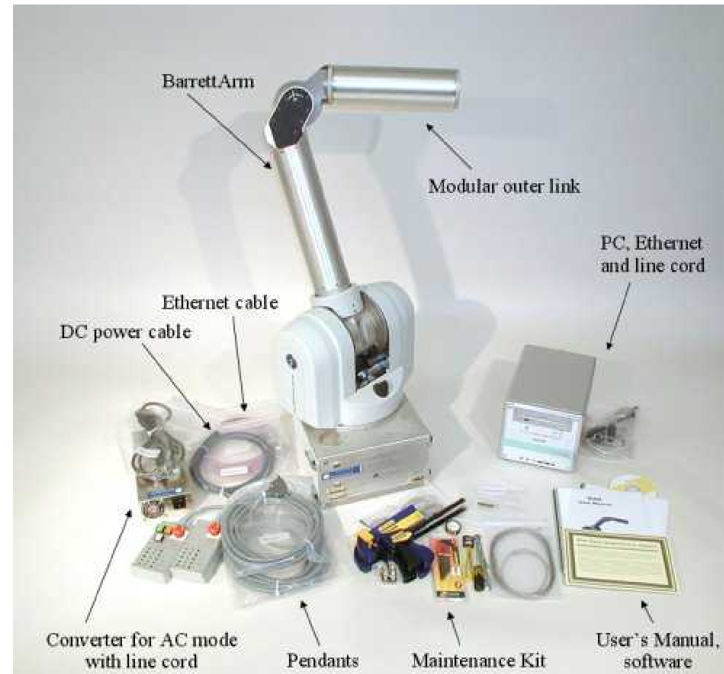
- **Released by robot arm, attaches to patient skin via active suction**
  - **Registered to patient rather than LSTAT to accommodate motion during transport**
- **Holds applicator and provides 6 cm x 6 cm planar motion, used for treatment and scanning multiple areas**
- **Permits 4 cm passive vertical travel to accommodate bolus actuation and curved surfaces**
- **Tethered for power, signals, suction, water**
- **Self-aligning attachment to arm**
- **Approx 18 cm square, 2.3 kg**





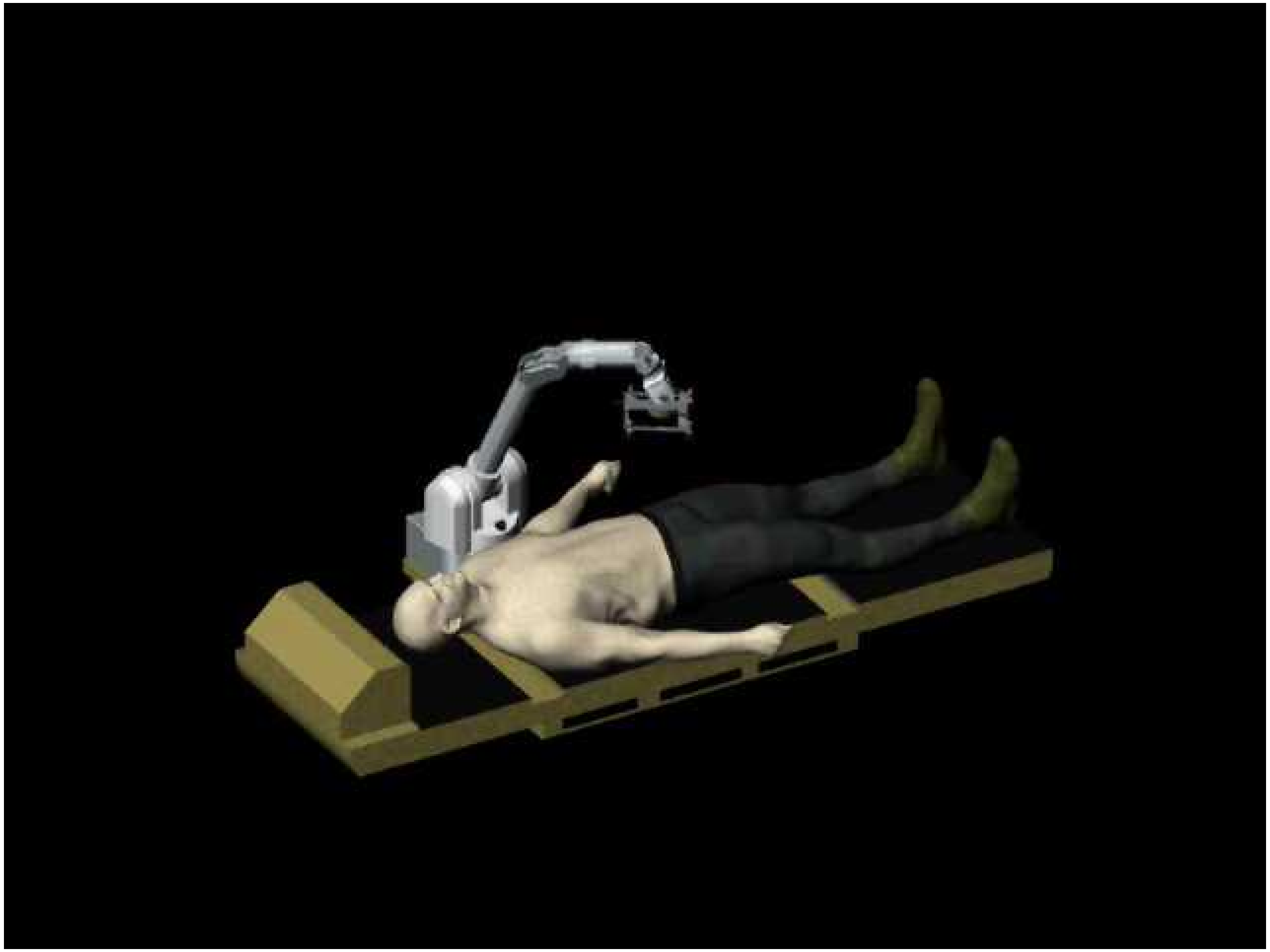
Robot Arm

- **WAM (whole arm manipulation) Arm from Barrett Technology**
  - **WAM means arm is responsive to contact along its entire length, not just at the end-effector**
- **Backdriveable, cable-driven system extremely safe for human contact under simple control**
  - **Appropriate for motion, force, impedance control**
- **7 DOF, 3 kg payload, 1 m reach**
- **Minimal external electronics, extremely compact system**



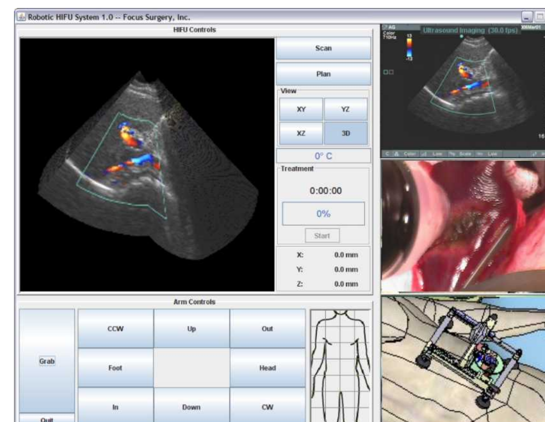
Barrett Technology, www.barretttechnology.com

System Operation



Design Updates and Progress

- For limb treatment, arm can move applicator directly against skin, without using end-effector (not shown in video)
  - Possible because arm is well-suited for physical interaction
  - Treatment performance will be better when end-effector used



- Phase 2: 10/06 – 9/08

- To date:
  - HIFU array and electronics complete
  - Drive components selected and ordered
  - Design refinement ongoing
  - Arm being manufactured
  - Operator interface complete

Principles for "Robotic Field Medics"

- Safe for physically-meaningful human contact
- Modular to maximize resources and simplify requirements on subsystems
  - One module for HIFU, one module for tourniquets, etc.
- Semi-autonomous remote control
  - Performing functions that are generally too complex to guide effectively with pure teleoperation
  - Visual processing, decision-making technology far too immature for autonomous treatment

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Acknowledgments

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  - The views, opinions and/or findings contained in this presentation are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.

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Extra Materials

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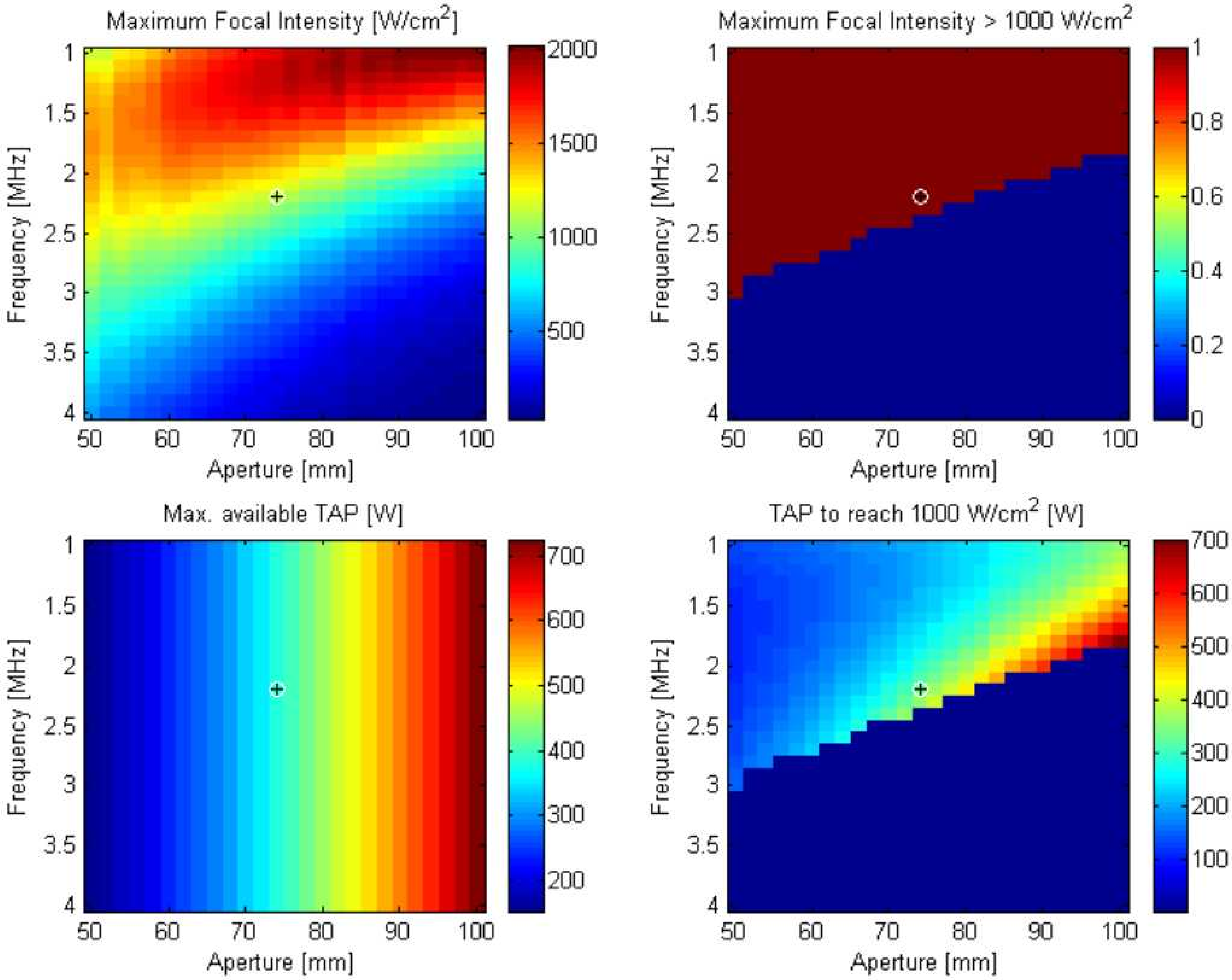
HIFU Phased Array Design



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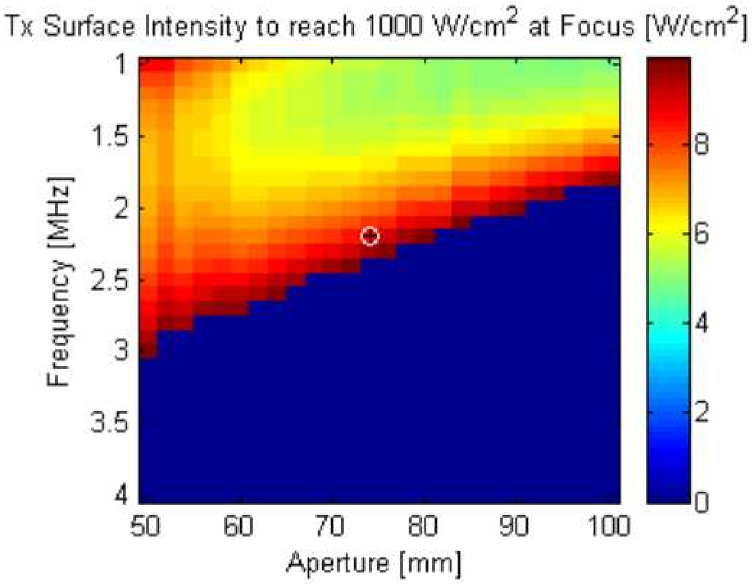
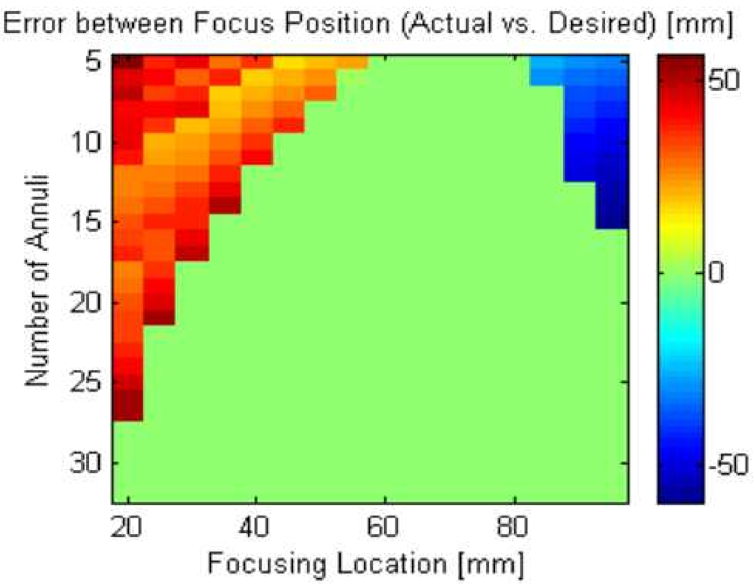
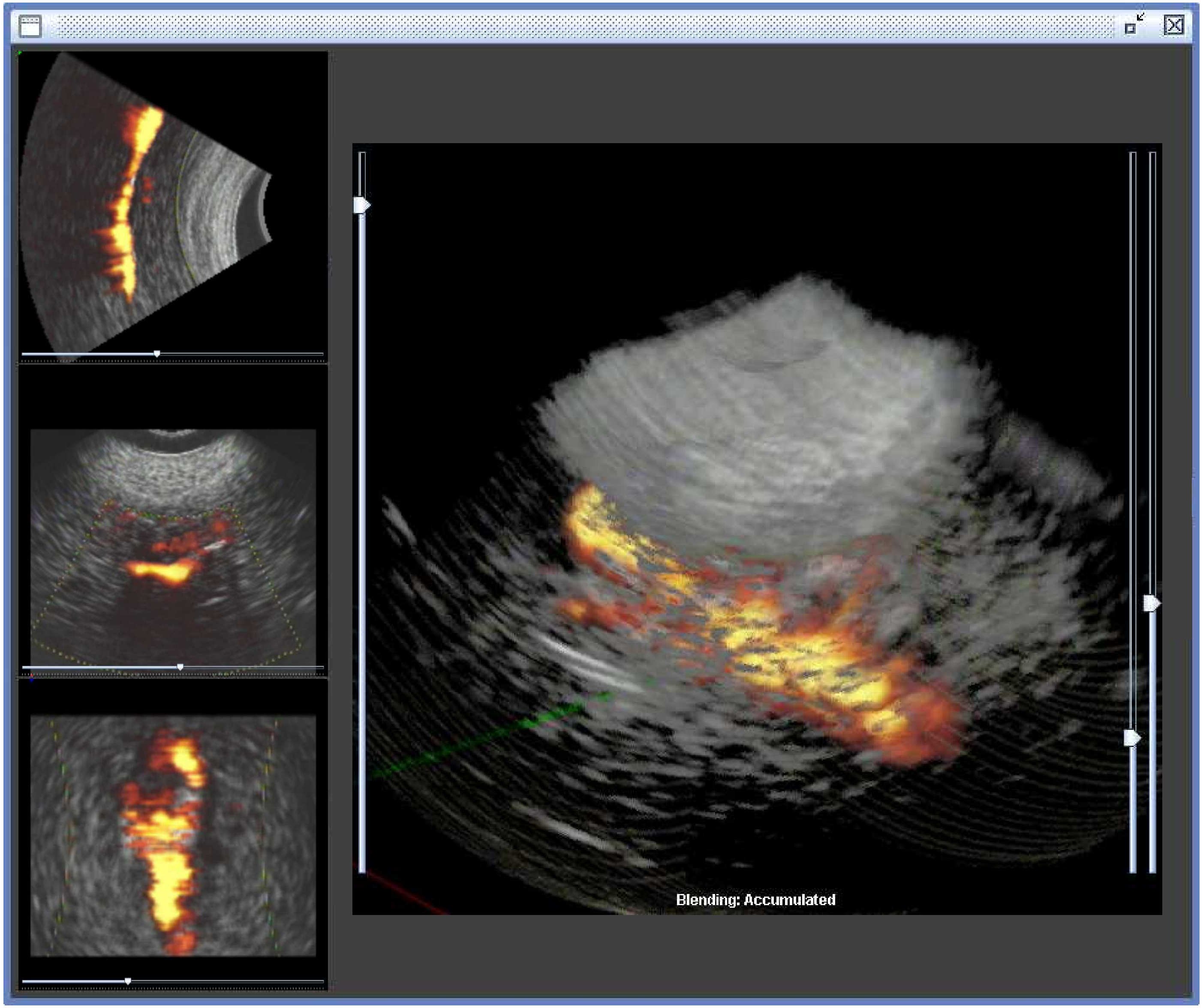
HIFU Phased Array Design





Laceration Detection using Doppler



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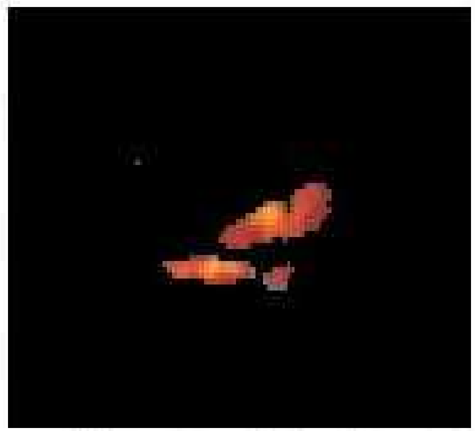
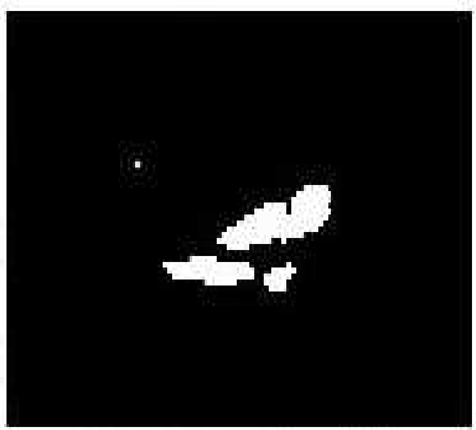
Treatment Planning Concept

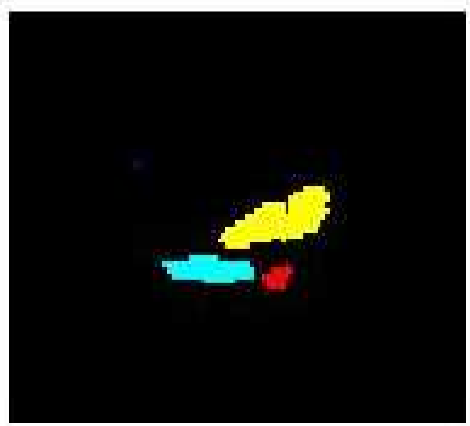
Input Data

Color Part





Flow Region



Labeled Region

- Visually position end-effector on wound (interactive)
- Attach end-effector to patient (autonomous)
- Scan volume under end-effector to locate laceration (autonomous)
- Segment and extract flow regions (autonomous)
- Label regions for treatment (interactive)
- Define scan path
- Execute cauterization run (autonomous)
- Monitor treatment progress, and repeat, as required (interactive)

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3D Image Construction

- **Spin-scan construction of 3D image from 2D slices**

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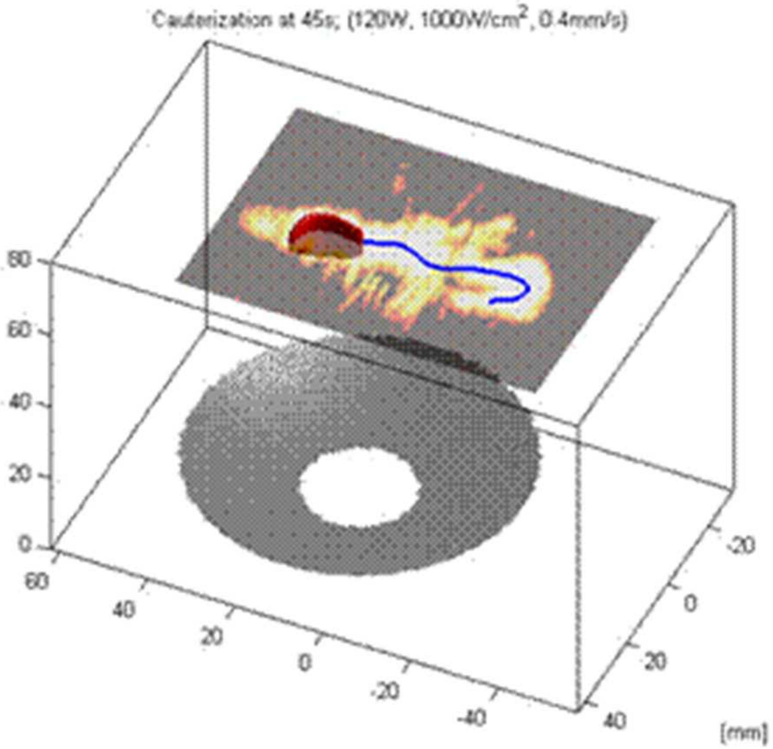
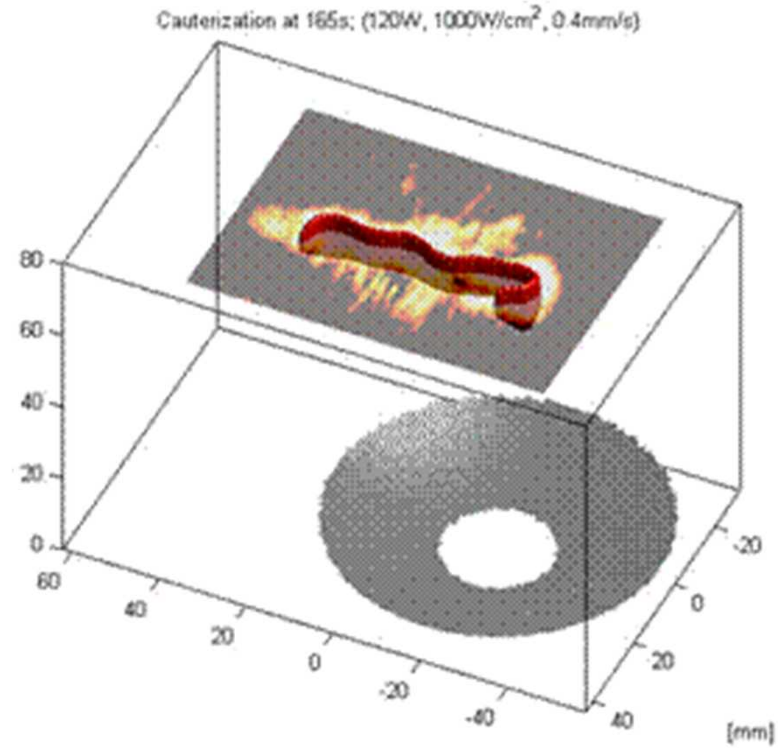
Vessel Cauterization using HIFU





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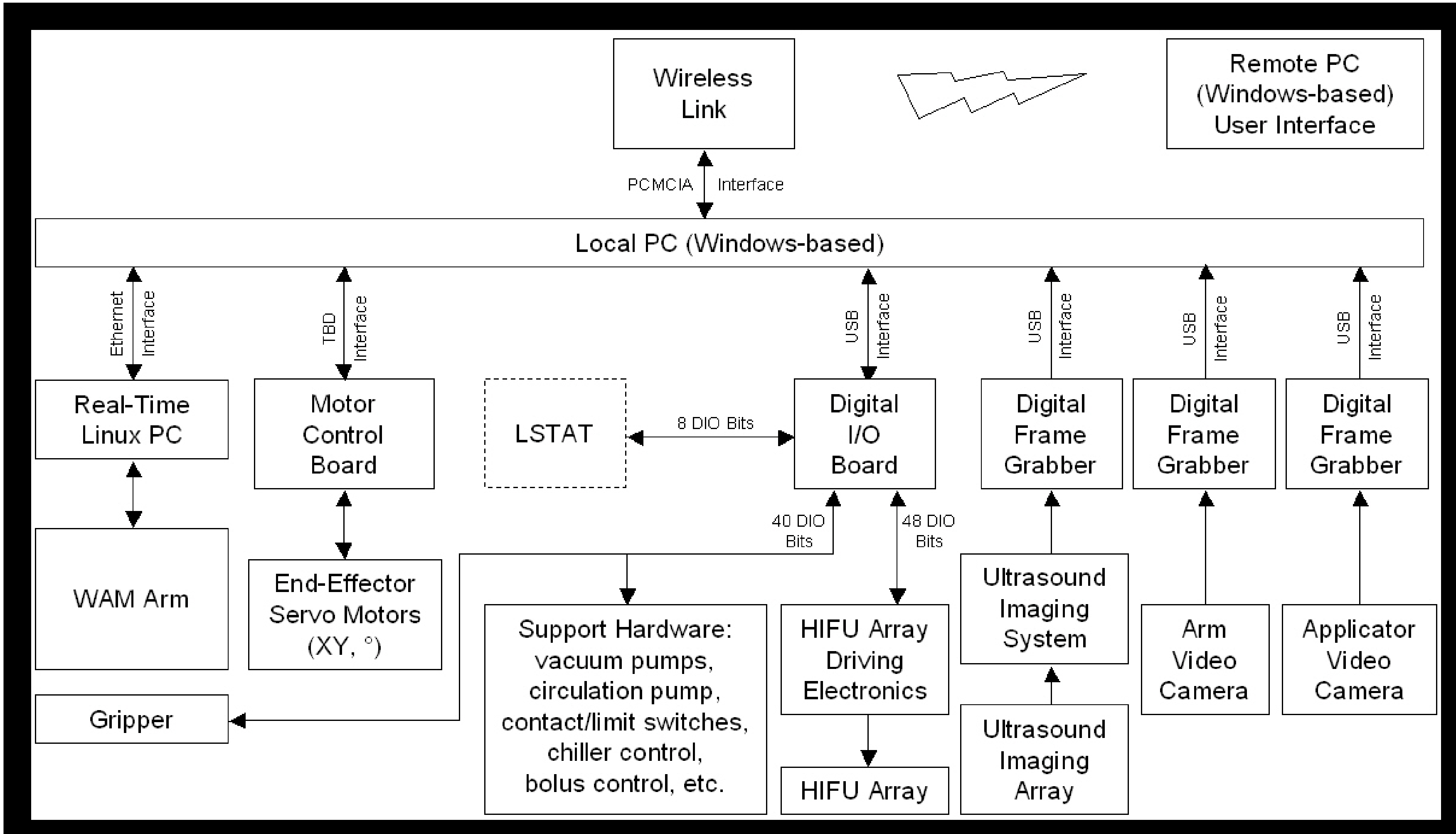
End-Effector Control Messaging Structure

Start Byte	Message Length	Message Type	Data Bytes	CRC Check
0xF6	1 Byte	1 Byte	n Bytes	1 Byte

Byte #	Applicator Control	Range	Scale
0	X-Position	0-6 [cm]	0.24 [mm]
1	Y-Position	0-6 [cm]	0.24 [mm]
2	Angle (low byte)	0-180 [deg]	0.003 [deg]
3	Angle (high byte)		
4	Linear Velocity	0-100 [%]	% of Max
5	Angular Velocity	0-100 [%]	% of Max
6	Pause Time	0-255 [sec]	1 [sec]

Control Architecture/Integration Block Diagram



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Power Budget

	Power	Power	Time	Time	Energy
	ON	Standby	ON	Standby	(period: 1 hr)
Description	[W]	[W]	[min]	[min]	[Wh]
HIFU System					
Annular Array (acoustic power)	120.0	0.0	15	45	
Low-Power Electronics	7.2	5.0	15	45	5.5
High-Power Electronics (to power the array)	250.0	0.0	15	45	62.5
Imaging System					
Hand-held Ultrasound Imaging with Doppler	45.0	20.0	45	15	38.8
Manipulator Arm Camera	3.3	3.3	60	0	3.3
End-Effector Camera	3.3	3.3	60	0	3.3
HIFU Transducer Camera	0.2	0.2	60	0	0.2
HIFU Transducer Lighting (5 White LED's)	0.5	0.0	60	0	0.5
Processing System					
1-2GHz Pentium PC	60.0	30.0	45	15	52.5
End-Effector System					
2-3 Motors	5.0	1.0	30	30	3.0
Robot Manipulator Arm					
Motors	45.0	27.0	15	45	31.5
Support					
Chiller	33.6	0.0	60	0	33.6
Circulating Pump	3.6	0.0	60	0	3.6
Volume Adjustment System	2.0	0.1	10	50	0.4
Spray Pump	3.6	0.0	10	50	0.6
4 Suction Pumps	10.0	0.0	50	10	8.3
RF-Link	4.0	2.0	50	10	3.7
Total:	**476.3**	**91.9**			**251.4**
	[W]	**[W]**			**[Wh]**

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