Representing Ultrasonic Maps Using Active Snake Contours

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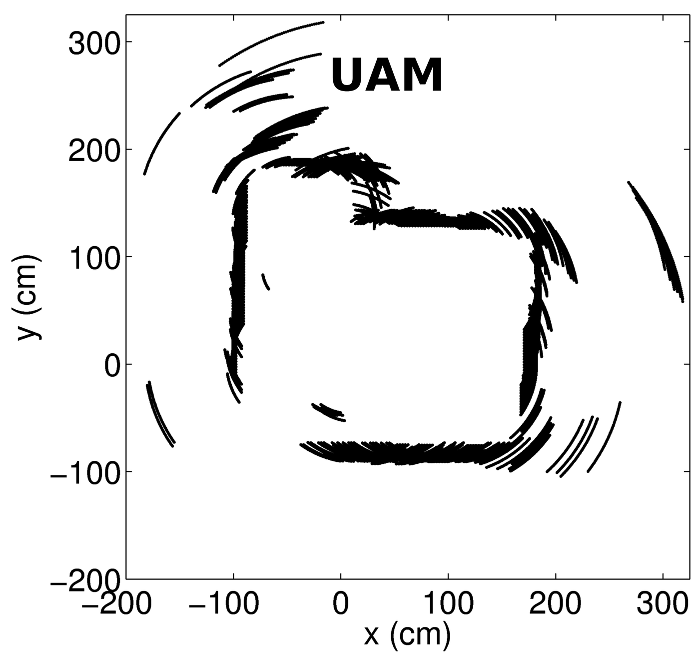
Introduction

- data from ultrasonic sensors are difficult to interpret because of:
  - large sensor beamwidth
  - multiple and higher-order reflections
  - cross-talk between sensors
- physical sensor models and intelligent processing techniques are needed to interpret and represent ultrasonic data properly

Ultrasonic Arc Map (UAM):



- collection of arcs spanning the sensor beamwidth at the measured ranges [1]
- UAMs can be processed by various techniques to improve accuracy of maps [2]
- resulting map still comprises a large number of points with possible outliers
- in this study, processed UAMs are represented parametrically to:
  - further eliminate the outliers
  - represent map points more compactly and efficiently

Euclidean Distance Transform (EDT)

Euclidean distance measure between two points $\mathbf{p}_i \in$ P and $\mathbf{q}_j \in$ Q:

$$d(\mathbf{p}_i,\mathbf{q}_j) = \sqrt{(p_{xi}-q_{xj})^2+(p_{yi}-q_{yj})^2+(p_{zi}-q_{zj})^2}$$

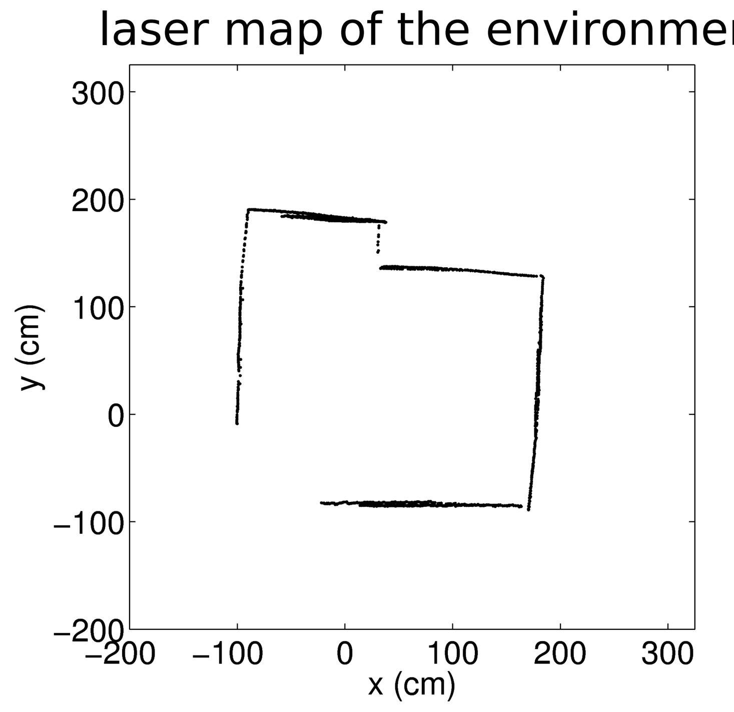
$$i \in \{1,\ldots,N_1\} \qquad j \in \{1,\ldots,N_2\}$$

Euclidean distance transform (EDT):

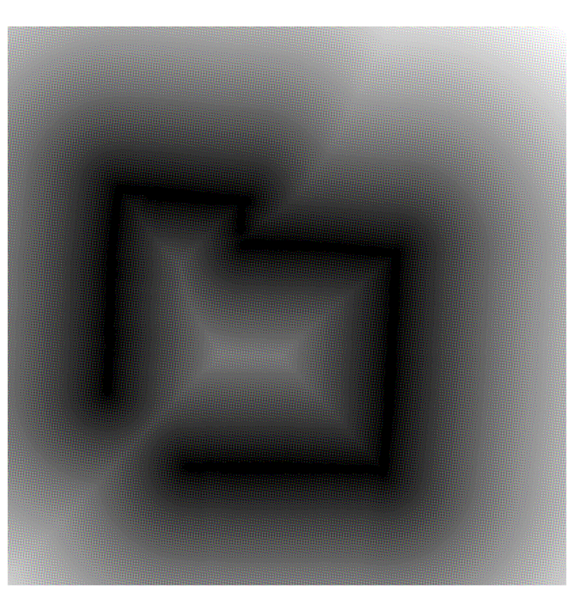
$$D_Q(\mathbf{p}) = \min_{\mathbf{q}_j \in Q}\{d(\mathbf{p},\mathbf{q}_j)\} \quad j \in \{1,\ldots,N_2\}$$

P : the set of all points in the environment
Q: the set of all map points acquired by a sensor

laser map of the environment



EDT



Active Contours (Snakes) [3]

A **snake** is a parametric curve $\mathbf{v}(s) = [x(s)\ y(s)]^T$ with **energy functional:**

$$E_{\text{snake}} = \int_0^1 [E_{\text{int}}(\mathbf{v}(s)) + E_{\text{ext}}(\mathbf{v}(s))]\, ds$$

($s \in [0,1]$: normalized arc length parameter)

- **internal energy** penalizes elongation (by α) and bending (by β):

$$E_{\text{int}}(\mathbf{v}(s)) = \frac{1}{2}\left(\alpha\left\|\frac{d(\mathbf{v}(s))}{ds}\right\|^2 + \beta\left\|\frac{d^2(\mathbf{v}(s))}{ds^2}\right\|^2\right)$$

- **external energy** is chosen as the EDT of the map
- **goal:** find the snake that minimizes **total energy** by solving the discretized Euler-Lagrange equations iteratively:

$$\mathbf{p}_x(n+1) = (\mathbf{A}+\gamma\mathbf{I})^{-1}\left(\gamma\,\mathbf{p}_x(n) - \kappa\left.\frac{\partial U}{\partial p_x}\right|_{[\mathbf{p}_x(n),\mathbf{p}_y(n)]}\right)$$

$$\mathbf{p}_y(n+1) = (\mathbf{A}+\gamma\,\mathbf{I})^{-1}\left(\gamma\,\mathbf{p}_y(n) - \kappa\left.\frac{\partial U}{\partial p_y}\right|_{[\mathbf{p}_x(n),\mathbf{p}_y(n)]}\right)$$

n: iteration step
α: elongation parameter
β: bending parameter
γ: Euler step size
κ: external force weight

$\mathbf{p}_x$, $\mathbf{p}_y$: coordinates of points on the snake
A: a penta-diagonal banded matrix depending on α and β
U: potential function (chosen as EDT)

Parameter Optimization

- snake parameters: α, β, γ, and κ
- parameter optimization methods used:
  - uniform sampling of 4-D parameter space
  - particle swarm optimization (PSO) [4]

method	α	β	γ	κ
uniform sampling	4.20	0.60	0.60	1.80
PSO	7.7	10.24	2.99	6.19

Results

generic error criterion:

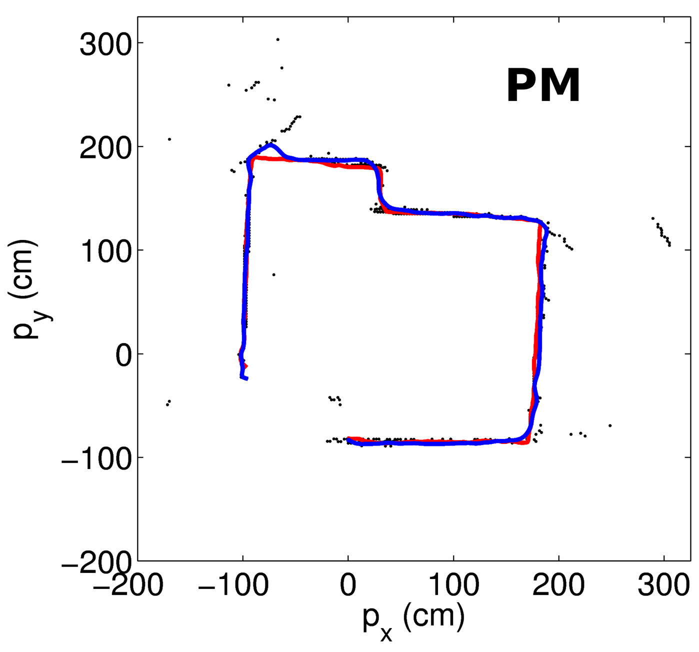
$$\mathcal{E}_{(P-Q)} = \frac{1}{2}\left(\frac{1}{N_1}\sum_{i=1}^{N_1} D_Q(\mathbf{p}_i) + \frac{1}{N_2}\sum_{j=1}^{N_2} D_P(\mathbf{q}_j)\right)$$

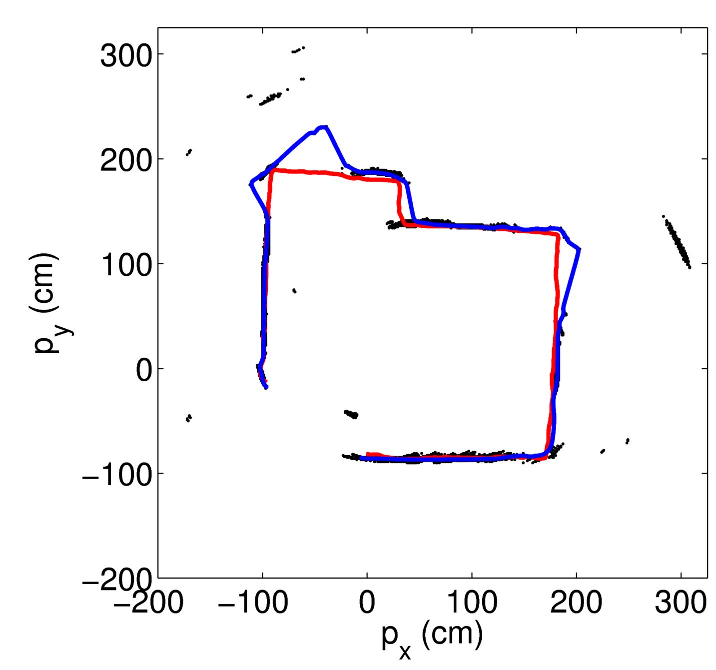
(``difference'' between two discrete point sets P and Q)

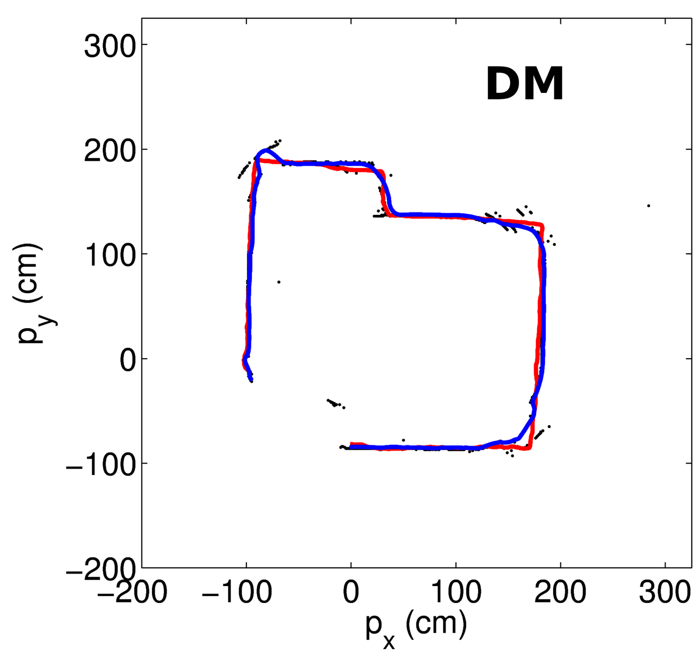
- P and Q may be chosen in many different ways
- snakes are fitted to point sets obtained with eight different UAM processing techniques [2]:

	PSO		uniform sampling	
	$\varepsilon_{(Sk-M0)}$	$\varepsilon_{(Sk-S0)}$	$\varepsilon_{(Sk-M0)}$	$\varepsilon_{(Sk-S0)}$
PM	3.00	2.65	2.71	**2.29**
VT	3.32	3.16	2.81	2.51
DM	**2.99**	**2.56**	**2.69**	2.63
MP	5.55	5.87	4.82	5.14
BU	6.24	5.71	5.89	5.35
ATM-org	3.53	3.15	2.97	2.58
ATM-mod	3.12	3.04	3.11	3.02
TBF	3.90	4.33	4.00	4.63

M_0: laser map (very accurate, considered as ground truth)
S_0 : snake fitted to the laser map
S_k : snake fitted to the points resulting from k^{th} UAM processing technique







(sample results are shown)

- processed UAM (black)
- snake fitted to processed UAM (blue) (uniform sampling)
- snake fitted to the laser map (red)

- **demonstrated that snakes can represent ultrasonic map points compactly and efficiently**
- **uniform sampling errors are in general smaller than PSO**
- **smallest errors achieved with DM and PM, largest with MP and BU**
- **applicable to point-based maps obtained with other sensing modalities (e.g., laser, infrared, radar)**

Acknowledgments

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References

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