Two-Stage Focused Inference for Resource-Constrained Collision-Free Navigation

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Two-Stage Focused Inference for Resource-Constrained Collision-Free Navigation

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Abstract—Long-term operations of resource-constrained robots typically require hard decisions be made about which data to process and/or retain. The question then arises of how to choose which data is most useful to keep to achieve the task at hand. As spacial scale grows, the size of the map will grow without bound, and as temporal scale grows, the number of measurements will grow without bound. In this work, we present the first known approach to tackle both of these issues.

The approach has two stages. First, a subset of the variables (focused variables) is selected that are most useful for a particular task. Second, a task-agnostic and principled method (focused inference) is proposed to select a subset of the measurements that maximizes the information over the focused variables. The approach is then applied to the specific task of robot navigation in an obstacle-laden environment. A landmark selection method is proposed to minimize the probability of collision and then select the set of measurements that best localizes those landmarks. It is shown that the two-stage approach outperforms both only selecting measurement and only selecting landmarks in terms of minimizing the probability of collision. The performance improvement is validated through detailed simulation and real experiments on a Pioneer robot.

I. INTRODUCTION

One of the core enabling capabilities for mobile robots operating in uncertain and GPS-denied environments is the ability to autonomously build a map and then subsequently use this map to achieve some objective. The required fidelity and choice of map representation are, in general, domain specific, and furthermore may not even be constant across a given application. Consider the following tasks:

- A robot is navigating through an uncertain environment consisting of some open areas and some narrow hallways.
- An autonomous car is operating on a road network consisting of highways and local roads.
- A marine robot is localizing a set of underwater mines amongst clutter.

In each of these cases, there is some notion of priority of landmarks in the map. In the indoor navigation scenario, it is more important to have accurate estimates of landmark locations in tight corridors to avoid collisions. Similarly on the road network, landmarks on more highly traveled roads are more useful \textsuperscript{1} and in the underwater scenario it is more important that the robot localize the mines as opposed to the clutter. Consequently, the robot can save resources, such as memory and computational effort, by focusing the mapping operation to more explicitly support the task.

Such complicated scenarios often require high dimensional models to represent robot poses, landmarks, and obstacles. Graphical models are a powerful tool in this case because they can explicitly represent conditional independences between variables resulting in fast inference on large scale problems \textsuperscript{2, 3, 4}. However naively applying these methods will result in an unbounded growth in memory and computational requirements, which will ultimately result in failure for a resource-constrained system.

Recent work on map reduction either uses some criterion to discard incoming measurements \textsuperscript{5, 6}, or selectively removes nodes from the graph through marginalization followed by a sparsification procedure to maintain efficiency \textsuperscript{7, 8, 9}. In all of these cases, the objective is map reduction while minimizing the impact on the overall quality of the map and robot trajectory.

This paper presents a more flexible map reduction framework that supports task-specific landmark prioritization. The framework is applied to the task of robot navigation and it is demonstrated that the procedure reduces the resource requirements without significantly impacting the task performance (navigation) by focusing on the important parts of the map.

The workflow is shown in Fig. 2. Assume that a prior data collection operation has been carried out. The next step is

Fig. 1: Localization of some landmarks is more important than others. In the figure, it is more important to localize landmarks in narrow hallways than large rooms. As a result, far fewer measurements (blue) are required for landmarks in the open area as compared with the narrow hallway. (Landmarks are red stars, gray dashed path is trajectory of robot. Black and red dashed ellipses represent uncertainty in robot position and landmarks position respectively.)

\textsuperscript{1}Useful here means useful for the specific task at hand.
Chow-Liu tree (CLT) approximation. Alternately, sparsity can be enforced through an $\ell_1$-regularization term in the KLD minimization [8], which is appealing because it does not impose a specific graph structure on the sparse approximation (e.g., a CLT). More recently, Mazuran et al. [9] improved upon previous methods by allowing non-linear measurements to approximate the dense subgraph which can be defined arbitrarily and then formulating the KLD minimization with respect to the measurement, rather than state, information matrix.

These graph reduction techniques are not concerned with selecting the nodes to be removed from the graph. Performance can degrade if the wrong landmarks are removed through marginalization since they are no longer available for subsequent loop-closures.

Front-end algorithms discard measurements before they are processed by the SLAM optimizer. Kretzschmar et al. [6] propose a pose-graph compression where laser scans are selectively removed by utilizing an approximate marginalization based on a CLT, and Ila et al. [5] use an information criterion to remove uninformative loop closures.

The method proposed in this paper is a front-end approach because it directly removes measurements (either incrementally or in batch). However, the key difference as compared to [5, 6] is that measurements are selected based on how useful they are to support localization of specific landmarks, which are selected to support a specific task (e.g., collision-free navigation).

B. Landmark Selection

The notion of selecting landmarks to support localization and/or mapping has been proposed to accomplish a number of different objectives. For example, Carlone et al. [13] use a measurement selection formulation to find a maximal set of coherent measurements in the hope that this coherent set will be outlier-free. Another popular application in vision-based systems is to down-sample landmarks based on some measure of visual saliency in the hope of improving loop closure detection. Specific applications include active gaze control [14], area coverage [15], and lifelong operation of service robots [16].

Fig. 2: Two-stage focused inference

to select the focused variables that are deemed important for task execution. Sec. IV discusses the specific case of selecting landmarks to support collision-free navigation. The third step is to select the subset of measurements that are most useful for estimating the focused variables, as described in general terms in Sec. III. The last steps are to build a map using the reduced set of variables and measurements, and then finally execute the desired task, in this case navigation. Note that in general the task may be executed many times, but the data only needs to be collected once.

In summary we claim the following contributions:

- A framework for measurement selection in the case that some variables are deemed higher priority than others (focused inference),
- A method for landmark (focused variable) selection to support the task of collision-free navigation,
- We show that focused inference over focused variables is able to minimize the probability of collision as compared to either in isolation.

II. RELATED WORK

This section reviews related work on SLAM map reduction, landmark selection and its application to autonomous navigation, and planning with uncertainty.

A. Map Reduction

Graph-based optimization approaches [10] have become popular for SLAM problems. These methods provide a naturally sparse representation of the SLAM problem that can be solved online efficiently [11]. Nevertheless, these methods do not scale constantly with time and space, and ultimately require some form of graph reduction to enable longterm operation. Such graph compression techniques can be separated into two main groups: those that incorporate each measurement and then selectively marginalize variables from the graph (SLAM back-end), and those that discard measurements directly (SLAM front-end).

In general, marginalization induces a fully connected subgraph over the Markov blanket of the marginalized variable. Most back-end map reduction approaches employ a convex optimization formulation, similar to the method introduced in [12] for sparsification, where the Kullback-Leibler divergence (KLD) between the dense subgraph and a sparse approximation is minimized subject to a consistency constraint. Carlevaris and Eustice [17] present a method called generic linear constraints that sparsifies the dense subgraph using a

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the probability of reaching a goal without collision, which inherently accounts for metric properties of the map, such as constrictions and tight corridors.

C. Planning with Uncertainty

This work specifically considers navigation under map and pose uncertainty as the motivating application for the focused inference framework. Much of the current literature addresses the problem of finding collision free paths in the presence of robot pose uncertainty assuming the landmark map is given. A standard measure in finding a safe path is to define a constraint on the measurement set: 

\[ f(\hat{x}|z^{R}) \]

\[ s.t. \quad g(z^{R}) \leq c \]  \hspace{1cm} (1)

Commonly used information metrics include entropy, mutual information, and KLD, and a common cost function is the cardinality of the set \( g(z^{R}) = K^{R} \).

Graphical models, such as the Markov random field (MRF) in Fig. 3 are a compact way of representing dependencies between variables\(^2\). For a MRF, the joint posterior can be expressed as a product of clique potentials, \( \psi_c(x_{|c}) \):

\[ p(x|z^{R}) \propto \prod_{c \in \mathcal{C}} \psi_c(x_{|c}) \]  \hspace{1cm} (2)

where \( \mathcal{C} \) is the set of all cliques, \( x_{|c} \) are the variables in clique \( c \). Because each clique potential \( \psi_c(x_{|c}) \) is strictly positive, \( p(X = x|z^{R}) \) can be written equivalently in logistic form:

\[ p(x|z^{R}) \propto \exp\left\{ \sum_{c \in \mathcal{C}} \phi_c(x_{|c}) \right\} \]  \hspace{1cm} (3)

where \( \phi_c(x_{|c}) = \log \psi_c(x_{|c}) \).

The reduction from the full set of variables to the focused variables is achieved by mapping the posterior through the prioritization function \( w(\cdot) \) to produce a new posterior over the focused variables:

\[ p(\tilde{x}|z^{R}) \propto \exp\left\{ \sum_{c \in \tilde{\mathcal{C}}} \tilde{\phi}_c(x_{|\tilde{c}}) \right\} \]  \hspace{1cm} (4)

where \( \tilde{\mathcal{C}} \) is the new (smaller) set of cliques over \( \tilde{X} \) and \( \tilde{\phi}_c \) are the resulting clique potentials.

If we define the function \( f(\cdot) \) in (1) to be the Shannon entropy of the conditional distribution:

\[ H(\tilde{x}|z^{R}) = \mathbb{E}_{\tilde{x}|z^{R}}[-\log p(\tilde{x}|z^{R})] \]  \hspace{1cm} (5)

This section leaves the formulation as general as possible with and then proceed to formulate the problem of measurement selection of focused variables has already been performed, \( \tilde{X} = \{\tilde{X}_1, \ldots, \tilde{X}_N\} \), with \( \tilde{N} \ll N \). To maintain generality, we represent the mapping from the unfocused variables to the focused variables by a prioritization function \( w(\cdot) : \mathbb{R}^{\tilde{N}} \rightarrow \mathbb{R}^{N} \). For example, in the degenerate case of landmark selection, \( \tilde{X} = w(X) = WX \) where \( W \) is an \( N \times \tilde{N} \) matrix with a single 1 in each row. However, the formulation allows for more complex mappings from the unfocused to the focused set.

\(^1\)The \( \sim \) notation is used throughout to refer to the focused set of variables.
where $\mathbb{E}$ is the expectation operator, then we obtain the resulting equation for the entropy of the focused variables, $X$ conditional on the subset of measurements $z^R$ as:

$$ f(\tilde{X};z^R) = H(\tilde{X}|z^R) = \mathbb{E}_{\tilde{X}|z^R}[ -\sum_{c\in C} \tilde{\phi}_c(\tilde{x}_{\{c\}})] + C \quad (6) $$

where $C$ is a constant.

It should be noted that computing the transformation from $\phi$ to $\tilde{\phi}$ may be hard in general. Furthermore, in general the graph over $\tilde{X}$ will be much denser than the graph of $X$, and computing $H(\tilde{X}|z^R)$ may be computationally expensive. However, it will be shown that $H(\tilde{X}|z^R)$ can be computed in closed form given two assumptions:

**Assumption 1.** The clique potentials can be approximated as Gaussian distributions.

**Assumption 2.** The prioritization function $w(\cdot)$ is an affine transformation.

Assumption 1 is, in fact, less limiting than the standard additive Gaussian noise assumption in the SLAM literature, since even in the case of robust cost functions we can always approximate the posterior as a Gaussian distribution using the Laplacian approximation [28]. Assumption 2 essentially requires the focused variables to be linear combinations of the original variables, which is still more general than other variable selection methods [17] which restrict the set of focused variables to be a strict subset of the original set.

### B. Gaussian Approximation of Clique Potentials

We begin by applying the standard method [29] of approximating a posterior over the unfocused variables (3) using a second-order Taylor series expansion of the potential functions $\phi_c$ at some initial guess $x^*$, and denote the approximated posterior as $\tilde{\phi}_c$: $p(x|z^R) \approx \tilde{p}(x|z^R) \propto \exp\{ \sum_{c\in C} \tilde{\phi}_c(x_{\{c\}}) \}$ for all $(x)$

$$ = \exp\{ \sum_{c\in C} \phi_c(x^*_{\{c\}}) + (x - x^*)^T \sum_{c\in C} \frac{\partial}{\partial x} \phi_c(x^*_{\{c\}}) + \frac{1}{2} (x - x^*)^T \left( \sum_{c\in C} \frac{\partial^2}{\partial x^2} \phi_c(x^*_{\{c\}}) \right) (x - x^*) \} \quad (7) $$

We note that the exponential component in (7) is quadratic in $x$, therefore the approximation is a Gaussian distribution with information matrix, $\Lambda_{z^R}$ given by the Hessian:

$$ \tilde{p}(x|z^R) = \mathcal{N}^{-1}(\zeta, \Lambda_{z^R}) , \Lambda_{z^R} = \sum_{c\in C} \frac{\partial^2}{\partial x^2} \phi_c(x^*_{\{c\}}) + C \quad (8) $$

which can be further decomposed in the case of single and pairwise cliques as:

$$ \Lambda_{z^R} = \frac{1}{2} \sum_{i,j=1}^N x_i^T A_{i,j} x_j \quad (9) $$

where $A_{i,j} \neq 0$ only if $i = j$ or $X_i$ and $X_j$ are connected in the graph. We write $\Lambda_{z^R}$ with subscript $z^R$ to explicitly represent that the information is dependent on the choice of selected measurements which will impact the structure of the graph and the resulting cliques.

One point of note is that $\Lambda_{z^R}$ is inherently dependent on the linearization point chosen $x^*$. For computational efficiency, we pick $x^*$ at the beginning and fix it for rest of the measurement selection procedure.

### C. Affine Prioritization Function

In Sec. III-A we defined the prioritization function $w(\cdot)$, which is a task-specific and predefined function that maps the set of all variables onto the set of focused variables. In this section we impose the restriction that this function is affine in order to provide a closed-form means of getting from (3) to (4):

$$ \tilde{X} = \tilde{w}(X) = WX, \quad (10) $$

where $W \in \mathbb{R}^{\bar{N} \times N}$. For example, in Fig. 4 we have:

$$ \begin{bmatrix} \tilde{X}_1 \\ \tilde{X}_2 \\ \tilde{X}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1/3 & 2/3 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} . \quad (11) $$

This restriction on the prioritization to be affine guarantees that the posterior over the focused variables will still be Gaussian: $	ilde{p}(\tilde{x}|z^R) = \mathcal{N}^{-1}(\tilde{\zeta}, \tilde{\Lambda}_{z^R})$. Furthermore, we can easily write an expression for the information matrix:

$$ \tilde{\Lambda}_{z^R} = (W\Lambda_{z^R}W^T)^{-1}, \quad (12) $$

as a result the approximate entropy of the focused variables given the selected measurements can be written in closed form:

$$ \hat{H}(\tilde{X}|z^R) = \frac{1}{2} \log |\tilde{\Lambda}_{z^R}| + C = \frac{1}{2} \log |W\Lambda_{z^R}W^T| + C \quad (13) $$

We finish by restating Problem 1 based on the Gaussian approximation and restriction to affine prioritization functions:

### Problem 2. Approximate Focused Measurement Selection

Select the subset of measurements $z^R = \{ z^R_1, \cdots, z^R_K \} \subset z$, such that approximate entropic information over the focused hidden variables $\tilde{X}$ is maximized, subject to the same constraint as (1):

$$ \max_{z^R \subset z} \quad -\log |W\Lambda_{z^R}^{-1}W^T| \quad \text{s.t.} \quad g(z^R) \leq c \quad (14) $$

### D. Efficiently Solving Problem 2

Each new measurement $z^R_k$ added to the set will introduce a new clique potential, $\phi_{k}(z^*_{\{k\}})$, into the joint posterior, where the set of variables $X_{\{k\}}$ are the ones affected by measurement $z^R_k$. We denote the intermediate set of $K \leq R^R$ measurements that have already been selected as $z^R_k = \{ z^R_1, \cdots, z^R_k \}$.

The approximate entropy reduction (or information gain) over the focused variables brought about by adding a new measurement $z^R_k$ is:

$$ \Delta \hat{H}(\tilde{X}|z^R_k) = \hat{H}(\tilde{X}|z^R_{k-1}) - \hat{H}(\tilde{X}|z^R_k) , \quad (14) $$

is the value that we want to maximize. In the following theorem we show that this quantity can be efficiently computed:
Algorithm 1 Measurement Selection for Prioritized Landmarks

Input: Initial information matrix $\Lambda_z$, focused variables $\hat{X}$, all measurements $z$, budget $c$

Output: measurements $z^R$

1: $k \leftarrow 0$, $z^{R_0} \leftarrow \emptyset$
2: while $g(z^{R_k}) < c$ do
3:      $k \leftarrow k + 1$
4:      $z^k = \arg\max_{z \in z^{R_{k-1}}} \Delta \tilde{H}(\hat{X}|z^k)$
5:      $z^{R_k} = z^{R_{k-1}} \cup \{z^k\}$
6:      $\Lambda_{z,k} = \Lambda_{z,k-1} + J_k J_k^T$
7:      $\Lambda_{z,k} = (W \Lambda_{z,k} W^T)^{-1}$
8: end while

IV. FOCUSED MAPPING FOR NAVIGATION

In this section, we return to the question of how to select the focused variables that are an input to the measurement selection scheme described in the previous section. The selection of focused variables mainly depends on the robot’s tasks and goals. Here we specifically consider the case of collision-free autonomous navigation.

The robot uses a map of landmarks to localize itself and navigate through an environment. To build the initial map, assume that a robot with image and depth/laser sensors (referred to as the data gathering (DG) robot) has been manually operated in the environment once to gather the initial dataset. The DG-robot’s trajectory can be represented as a sequence of random variables $X = \{X_1, \cdots, X_T\}$. In GPS-denied environments $X$ is not directly observable. However, the robot can always measure the incremental change between two sequential poses (odometry), for example from an IMU or wheel encoder.

There also exists a set of landmarks from which focused landmarks can be selected. Denote the set of landmarks as $L = \{L_1, L_2, \cdots, L_N\}$.

A. Selection of Focused Landmarks

While it could be possible to have thousands of landmarks, often a small, carefully chosen subset can lead to sufficiently accurate navigation. In particular, for resource-constrained systems, reducing the number of landmarks will significantly reduce the computation required for data association, which will in turn enable faster and more efficient on-line trajectory planning and navigation.

Narrow passages are challenging for collision-free autonomous robot motion planning. However, in the case of high map and robot uncertainty, the “narrowness” should be redefined. For example, a “geometrically” wide passage might still be problematic for a robot that does not have access to accurate landmark information and thus has poor localization accuracy. We refer to this passage as being “geometrically wide” but “probabilistically narrow” and we will formalize these terms below.

The evaluation of probabilistic narrowness involves two key components: 1) Calculating an estimate of the robot’s position uncertainty and 2) Calculating the probability of collision based on the robot’s uncertainty and the distance to obstacles as determined by the DG-robot.
1) Robot position uncertainty: To generate a path-independent estimate of the robot’s position uncertainty at any given point \( x \) along the robot’s path, we use the concept of belief stabilization introduced in \([30]\). Assume we have a closed-loop controller that can stabilize the system to \( x \) in which the landmarks viewable during stabilization are fixed (this assumption can be relaxed, c.f. \([31]\)). Such a controller is typically comprised of an estimator and a separated controller. The estimator generates an a posteriori distribution over all robot poses based on the existing map of landmarks and the local observation of landmarks. Given these estimates, the separated controller will generate a control signal that drives the robot toward \( x \). To design an analytic measure of narrowness we rely on a simple Linear Quadratic Gaussian (LQG) controller which is comprised of a Kalman filter as the local observation of landmarks. Given these estimates, the separated controller will generate a control signal that drives the robot toward \( x \).

The measurement model at point \( x \) is:

\[
\{\Sigma^* = Q + A(\Sigma^* - \Sigma^*HT(H\Sigma^*HT + R)^{-1}H\Sigma^*)AT\}_{x} \tag{19}
\]

The Jacobsians, \( A \) and \( H \) are computed by linearizing the measurement model at point \( x \) on the path, where \( Q \) and \( R \) are the process and measurement noise respectively. We associate with each pose \( x \) a set of visible landmarks \( L(x) \). The value of the steady-state covariance will be dependent on the set of visible landmarks as expressed through the measurement noise covariance \( R \). Note that Jacobian matrices and set of visible landmarks would be different for different points on the path. The main computational advantage in using this measure is that \( \Sigma^*(x) \) only depends on \( x \) not the path that leads to \( x \).

2) Collision probability: Using \( N(x_t, \Sigma^*(x_t)) \) as a path-independent measure of uncertainty for each point \( x_t \) on the path, the collision probability can be computed by a Monte Carlo method: for each \( x_t \) sample the normal distribution and count the number of samples that fall into the obstacle region. However, we propose an alternate method that utilizes an approximate measure and is computationally cheaper. We simply approximate the probability of collision, \( P_c \), as the Mahalanobis distance between \( x_t \) and the closest obstacle point.

In other words, \( P_c \) measures how many standard deviations obstacles are away from the mean of the distribution over \( x_t \):

\[
P_c(x_t) = (x_t - x_t^{\text{obst}})^T(\Sigma^*(x_t))^{-1}(x_t - x_t^{\text{obst}}) \tag{20}
\]

where the relative vector \( x_t - x_t^{\text{obst}} \) is the smallest reading received from the laser range finder in its local frame.

The landmark selection problem is framed as finding the poses along the trajectory with the highest collision probability then select landmarks that can reduce this pose’s uncertainty.

**Problem 3. Minimum Collision Probability Landmark Selection**: Select the \( \alpha \) landmarks \( L_f \subset L \), such that the maximum probability of collision is minimized:

\[
\min_{L_f \subset L} \max_{x_t \in L_f} P_c(x_t) \quad \text{s.t.} \quad |L_f| \leq \alpha \tag{21}
\]

---

**Algorithm 2 Minimum Collision Probability Landmark Selection**

**Input**: Robot poses \( X \), landmarks \( L \), odometry noise \( Q \), measurement noise \( R \), budget \( \alpha \)

**Output**: Selected landmarks \( L_f \)

1: \( k \leftarrow 0 \), \( L_k^0 \leftarrow \emptyset \)
2: Compute \( P_c(x_t) \) for all \( x_t \in X \) by \([19]\) and \([20]\)
3: \( P(l) = \max_{x_t \in X} P_c(x_t) \) for all \( l \in L \)
4: while \( k < \alpha \) do
5: \( k \leftarrow k + 1 \)
6: \( l_k^* \leftarrow \arg\max_{l \in L \setminus L_{k-1}} P(l) \)
7: \( L_f^k = L_f^{k-1} \cup \{ l_k^* \} \)
8: update \( P_c(x_t) \) for \( x_t \) that can observe \( l_k^* \)
9: update any \( P(l) \) that may have changed
10: end while

The problem is solved by greedily selecting landmarks. At each iteration, pick the landmark \( l^* \) that is associated with maximal \( P_c(x_t) \), then update \( P_c(x_t) \) for all the \( x_t \) that can observe \( l^* \). The algorithm is summarized in Alg. 2 Since the number of poses that can observe any individual landmark is low, this greedy approximation can be computed efficiently.

**B. Focused Measurement Selection for Navigation**

Here we detail how to apply this landmark selection scheme resulting from solving Problem 3 to the measurement selection process described in Sec. III. Recall that the joint log probability of an MRF is proportional to the sum of its potentials \( \phi(X_c, L_c|o, z) \):

\[
p(X, L) \propto \exp(\sum_{c \in C} \phi_c(X_c, L_c|o, z)). \tag{22}
\]

An odometry measurement, \( o \), adds a potential between two subsequent poses \( \phi_t(X_t, X_{t+1}; o_t) \) and a landmark measurement, \( z \), adds a potential between a pose and a landmark \( \phi_l^z(X_t, L_i; z^i) \).

The focused variables are selected focused landmarks: \( \tilde{X}_c = L_f \subset L \). Denote the rest of un-focused landmarks and robot poses as \( \tilde{X}_c = \{ L \setminus L_f, X \} \); then the affine prioritization function represented by \( W \) is

\[
\tilde{X}_c = W \begin{bmatrix} L_f \leftarrow \tilde{X}_c \end{bmatrix}, \quad W = [ I_{N \times N} \quad 0_{N \times N - N} ] \tag{23}
\]

If we apply the standard assumption that the odometry and landmark measurement are corrupted by additive Gaussian noise \([10]\), then the potentials are:

\[
X_0 \sim \mathcal{N}(\mu_0, \Sigma_0), \quad X_{t+1} = f(X_t, o_t) + \eta, \quad \eta \sim \mathcal{N}(0, R_t)
\]

\[
\phi_t(x_t, x_{t+1}) = -\frac{1}{2} (x_{t+1} - f(x_t, o_t))^T R_t^{-1} (x_{t+1} - f(x_t, o_t))
\]

\[
z_l^i = g(x_t, l_i) + \nu, \quad \nu \sim \mathcal{N}(0, Q_t, l_i)
\]

\[
\phi_l^z(x_t, l_i) = -\frac{1}{2} (z_l^i - g(x_t, l_i))^T Q_l^{-1} (z_l^i - g(x_t, l_i))
\]

Now the \( W \) matrix and the potentials can be used in Alg. 2 for the second stage: focused measurement selection.

**V. Navigation**

The final step is to actually use the reduced map to navigate with a resource constrained robot.
The built map is represented by a set of stochastic landmarks $L \sim \mathcal{N}(\bar{L}, R^L)$. Denote the desired trajectory to $T$ steps as $(x^d_t)_{t=0}^T$. Assume the robot starts at $x_t \sim \mathcal{N}(\bar{x}_0, \Sigma_0)$. Represent the control problem as:

$$
\min_{u(\cdot)} J = \mathbb{E} \left[ \sum_{t=0}^{T} (x_t - x^d_t)^T W_x (x_t - x^d_t) + u_t^T W_u u_t \right]
$$

$$
x_{t+1} = f(x_t, u_t) + w_t, \quad w_t \sim \mathcal{N}(0, Q_t)
$$

$$
z_t = h(x_t, L) + v_t, \quad v_t \sim \mathcal{N}(0, R_t), \quad L \sim \mathcal{N}(\bar{L}, R^L)
$$

where $W_x$ and $W_u$ represent the cost for robot states and control inputs. $Q_t$ and $R_t$ represent process and measurement noise respectively. The system is first linearized at the nominal trajectory $(x^d_t)_{t=0}^T$:

$$
x_{t+1} = x^d_{t+1} + A_t(x_t - x^d_t) + B_t u_t + w_t
$$

$$
z_t = h(x^d_t, \bar{L}) + H_t(x_t - x^d_t) + M^L_t h(L - \bar{L}) + v_t
$$

where $A_t$, $B_t$, $H_t$ and $M^L_t$ represent the Jacobian of $f(\cdot)$ and $g(\cdot)$ at the linearization point. The optimization of the linearized system can be obtained by a Kalman filter and a LQR controller. The equivalent measurement noise covariance for the Kalman filter is:

$$
\bar{R}_t = (M^L_t)^T R^L M^L_t + R_t
$$

which incorporates both the landmark uncertainty as $(M^L_t)^T R^L M^L_t$ and measurement noise $R_t$. The LQR controller will have the following form:

$$
u_t = -(B_t^T S_t B_t + W_u)^{-1} B_t^T S_{t+1} A_t (\hat{x}_t^+ - x^d_t)
$$

where $\hat{x}_t^+$ is the estimated mean at the $t$-th time step and $S_t$ is obtained by solving a discrete algebraic Riccati equation.

A more general and detailed description of navigation is presented in the supplemental material.

VI. EXPERIMENTS

Both simulation and real world experiments were done to test the proposed algorithms.

A. Simulation

Fig. 5 shows the simulation environment. We performed repeated trials in the simulation environment to test the ability of our proposed scheme to be able to navigate from a start point without collision. In total there are 74 landmarks (black stars), which the robot can observe with a range/bearing measurement if landmark is in the robot’s field of view. We assume that our resource constrained robot has a budget of $\alpha = 30$ landmarks (Alg. [2]) and $R^K = 90$ measurements (Alg. [1]). We compare six cases: (1) **optimal**: all landmarks and all measurements; (2) **focus, all**: focused landmarks and all measurements; (3) **focus, info**: focused landmarks and measurements selected based on information gain (our proposed method); (4) **focus, DS**: focused landmarks and uniform downsampling of measurements; (5) **full, info**: all landmarks and measurements selected based on information gain; (6) **full, DS**: all landmarks with uniform downsampling of measurements. Case (1) violates both stated budgets and should be seen as a lower bound on possible performance. Case (2) violates the $R^K$ budget but gives a lower bound on the attainable localization accuracy.

![Fig. 5: Navigation with focused landmark selection and map building. Green circles represent selected landmarks with their size representing uncertainty. Blue lines are the nominal trajectories each robot wants to follow with red circles representing pose uncertainty. The focused approach has much less uncertainty in narrow passages, thus lower collision probability compared to the unfocused case of the focused set. Cases (5) and (6) violate the $\alpha$ budget but, as we show, actually results in much poorer overall performance since the measurement budget is still respected and consequently all landmarks are localized indiscriminately resulting in unnecessary landmark estimate precision in wide corridors where it is not needed.](image-url)
### TABLE I: Comparison of simulated mapping results

<table>
<thead>
<tr>
<th></th>
<th>No. observed lms</th>
<th>No. focused lms</th>
<th>Entropy on focused lms</th>
<th>Error on all observed lms</th>
<th>Error on focused lms</th>
</tr>
</thead>
<tbody>
<tr>
<td>optimal</td>
<td>74</td>
<td>30</td>
<td>-61.3362</td>
<td>0.0204</td>
<td>0.0206</td>
</tr>
<tr>
<td>focus, all</td>
<td>30</td>
<td>30</td>
<td>-54.7506</td>
<td>0.0303</td>
<td>0.0303</td>
</tr>
<tr>
<td>focus, info</td>
<td>30</td>
<td>30</td>
<td>7.9911</td>
<td>0.3872</td>
<td>0.3872</td>
</tr>
<tr>
<td>focus, downS</td>
<td>30</td>
<td>26</td>
<td>66.6130</td>
<td>2.8026</td>
<td>2.8026</td>
</tr>
<tr>
<td>full, info</td>
<td>74</td>
<td>30</td>
<td>39.9598</td>
<td>22.3963</td>
<td>25.5736</td>
</tr>
<tr>
<td>full, downS</td>
<td>44</td>
<td>19</td>
<td>100.9545</td>
<td>2.0227</td>
<td>2.0456</td>
</tr>
</tbody>
</table>

30 landmarks were selected as focused based on the collision probability and 90 measurements are selected to optimize the graph. The proposed focused mapping has significant lower uncertainties and is closest to bounds given by case (1) and (2).

(a) is that the robot uncertainty is preferentially reduced in the areas of the environment where the corridors are tight and there is a higher chance of collision.

We further compare all six cases from a mapping perspective in Table I based on three metrics: the entropy of the focused landmarks, the error of all of the observed landmarks, and the error of the focused landmarks (which will be the same as the previous in all cases where only focused landmarks are being estimate). From the proposed focused two-step landmark and measurement selection approach achieves the best performance.

### B. Hardware experiment

In the real-world experiment, we ran a Pioneer robot in a cluttered office space. The robot is equipped with an RGB camera and a 270 degree field of view laser range finder. Figure 6 shows the floor plan of the environment. AprilTags were put up to create an initial pool of landmarks. The odometry measurements are obtained by matching consecutive laser scans using the open source canonical scan matcher. The landmark measurements are obtained by running the AprilTag detector with the RGB images, which gives the relative orientation and range of the tags in the robot’s frame. A summary of the dataset is in Table II. The selected measurements and odometry information are then fed into a standard SLAM solver g2o to optimize the graph. It is important to note that we did not use the laser for the full SLAM solution, only for generating reliable odometry measurements.

#### TABLE II: Office Dataset

<table>
<thead>
<tr>
<th>length</th>
<th># odometry measurements</th>
<th># landmark measurements</th>
<th># landmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>76</td>
</tr>
</tbody>
</table>

Fig. 6: Floor plan

Fig. 7: Information gained

Fig. 8: Mapping results. Color line represent robot’s risk of collision. Magenta circles represent landmarks with the size representing its uncertainty. The proposed two-stage approach (Focus,Info) outperforms either measurement reduction (Full, Info) or landmark reduction (Focus, DownS) isolated.

### VII. CONCLUSION

This paper presented a two-stage landmark and measurement selection procedure for resource-constrained robots operating in unknown or uncertain environments. In the first stage, a set of focused variables is selected that are most important for accomplishing a specific task. The second stage, measurements are selected to maximize the information gain on these focused variables. The two-stage procedure is then applied to the task of collision-free robot navigation in an obstacle-laden environment. Simulation and hardware results demonstrated that the approach can identify a relevant subset of landmarks and accurately localize them to reduce the probability of colliding with obstacles as compared with only landmark selection or measurement selection in isolation.
ACKNOWLEDGMENTS

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