Overview
Autonomy has made great strides over the history of robotics, dramatically decreasing physical and cognitive workload of operators and increasing task performance. However, autonomy has yet to surpass the adaptability and high-level cognitive reasoning of a human operator. It is therefore desirable to devise novel methods of effective human-robot collaboration (HRC) that take into account the strength of both autonomy and human operation by detecting scenarios difficult for autonomy and weighting that difficulty against operator workload. Robot controller design is usually hierarchical with both high-level task and motion planning and low-level control law design. Presented here are two methods for low-level and high-level control designs, respectively, to guarantee joint performance of HRC systems.

Suboptimal HRC for Guidance and Navigation
In the low-level method, the switched linear quadratic regulator (SLQR), an optimal control policy based on a quadratic cost function, is used taking into account system dynamics and operator workload.

Value Function:

\[ V_k(x_k) = \min_{u_k} Z_k^T P Z_k + \sum_{i=0}^{k-1} Z_i^T Q Z_i + U_k^T R U_k \]

where:

- \( X = [\Delta x, \Delta \dot{x}, \Delta y, \Delta \dot{y}, \Delta z, \Delta \dot{z}] \), error states
- \( U = [\Delta \alpha, \Delta \beta, \Delta \phi, \Delta \theta, \Delta \psi, \Delta \theta] \), error inputs
- \( A, B \) = linearized AUV state and input dynamics
- \( y = \text{workload} \)

Cost Function:

\[ U_k = b_k \cdot \text{1 (manual) or 0 (autonomy)} \]

Simulation Results
(Left) Under pure autonomy, the system cannot compensate for the unknown cross current.
(Below) Using SLQR to choose between manual control \((\sigma = 1)\) and autonomy \((\sigma = 2)\), system successfully navigates through the environment \((a)\), with switching scheme outlined by time \((b)\) and position \((c)\).

HRC for Safe Symbolic Motion Planning
In the high-level approach, formal methods are applied to a scenario where an operator oversees a group of mobile robots as they navigate an unknown environment. Autonomy uses specifications written in linear temporal logic (LTL) to conduct symbolic motion planning in a guaranteed safe but conservative approach.

The human operator can produce more efficient paths but is less safe due to incomplete environmental information.

Simulation Results
One operator collaborating with three robots in an unknown environment.

Simulation start
- Initial plans are generated
- Operator paired with Robot 2 and makes a plan
- Robot 2 loses trust from near miss
- Operator paired with Robot 1 and makes a plan

Conclusions
Incorporation of HRC into the controller hierarchy takes advantage of the benefits of both human and autonomy. Future works will expand upon this concept to study the advantages of having HRC at multiple control levels simultaneously.

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