Motivation

There exists a growing demand for heavy lift aerial transportation systems. Most research and development focuses on the creation of larger, more powerful and expensive lifting vehicles, such as Boeing’s JHL-40 (Skyhook). These systems accomplish the task by scaling up existing technology to provide increased payload capability but unfortunately at increased complexity and cost.

As the vehicles become larger, more attention needs to be paid to the structural dynamics. Larger airframes result in slower, significant vibrational modes which couple into the rotation and translation dynamics. The ensuing higher-order system requires study and simulation to guarantee safety and adequate performance.

An alternative approach would be to possibly use smaller, existing unmanned autonomous helicopters working cooperatively to perform the same task. This proposed system would provide a scalable solution that can be tailored to suit any assignment. Using smaller helicopters places more emphasis on the team strategy and control rather than the control of the individual helicopter. It may also be possible to reduce load swings during transport through the use of distributed connections.

Using a distributed solution such as this also allows for improved sensing capabilities. The sensing capability of one agent can be dramatically increased by incorporating other agent information. Therefore, by working together agents can achieve the high precision necessary for control.

Statically Indeterminate System

Lifting a load using helicopters has been studied and possible solutions have been proposed using specialized control architectures, support structures and passive control devices [Menon et al. 1988, Ciclani & Kanning 1992]. Although these solutions have been shown to work in practice, they are ultimately limited by the number of helicopters that can be employed.

Bemard and Kondak have successfully implemented a three helicopter transport team. This is believed to be the first time an autonomous group of helicopters has lifted a load. Although novel and impressive, we believe the real challenge occurs when more helicopters are added.

To illustrate the problem with increasing the number of lifters, we can look at the differences between a four-legged and a three-legged stool, shown in Figure 2. Unless all four legs of the stool are made to the exact specification, the stool will wobble. The three-legged stool does not have this problem, for any leg configuration the stool will remain stable. The four-legged and three-legged stools are said to be statically indeterminate and statically determinate, respectively.

For helicopters in two dimensions the position of the load can be uniquely determined by the position of the two lifters. However, when a third lifter is added, the problem changes significantly. When the lifters are modeled as inelastic cords, the lifters become holonomic constraints. Therefore, each lifter may only move on a circle given by the load connection point and the length of the tether. Should a lifter move to a point off of the circle then the system changes, see Figure 3. With a small perturbation one or two of the lifters can become slack, thus rendering the associated lifters ineffective, possibly causing the full system to become unstable.

Distributed Impedance Control

The goal of impedance control is to control the motion of interacting systems as well as modulate, regulate and control the dynamic interaction between the systems [Hogan 1985]. Originally devised by Hogan for use with robotic manipulators it can be extended to any dynamically interacting system.

In the case of heavy lift helicopter teams, the goal is to apply the correct force to the load to follow a desired trajectory while maintaining a stable helicopter configuration. Since the general case is a statically indeterminate problem, we cannot simply use position control to apply the correct forces on the load. To ensure the proper load distribution and avoid overloading, the dynamics between the helicopter and load need to be regulated. Therefore, impedance control is a natural fit for this application.

Figure 1 - Proposed Heavy Lift Helicopter System

Figure 2 - Indeterminate vs Determinate Structures

Figure 3 - Three Lifting Helicopters

Figure 4 shows a simplified heavy lift helicopter system under impedance control. To simplify the control structure, we are using a stiffness and viscous impedance given by

\[ u = K (\dot{x}_0 - x) - B \dot{x} \]

where \( u \) is the control input, \( K \) is the spring stiffness, \( B \) is the damper viscosity and \( x \) and \( \dot{x} \) are the commanded and actual helicopter positions, respectively. More elaborate impedances can be used to improve stability and performance; the impedance does not need to be linear nor constant, a time varying impedance is possible.

Since this control design relies heavily on position measurements, its sensitivity towards measurement error should be evaluated. The plots below show the load and helicopter positions in two dimensions using a soft and stiff impedance undergoing motion caused by position measurement error on the middle helicopter. We can see that given a desired level of performance, the impedance should depend on measurement accuracy. Future work will focus on the optimal impedance selection to guarantee stability and achieve the desired performance.

Figure 4 - Impedance Controlled System

Figure 5 - Impedance Sensitivity to Measurement Error

References

M. Bernard and K. Kondak, Generic Slung Load Transportation System Using Small Size Helicopters, IEEE International Conference on Robotics and Automation, May 10-17, 2009, Kobe Japan