The Kinect is remarkably proficient at its intended task, although when mounted on a moving base like Harlie, the Kinect is outside of its design parameters.

The Kinect has a limited field of view (57 degrees). The Kinect was designed to track users from a fixed vantage point, and has trouble when used from a mobile vantage point. The Kinect is especially sensitive to sudden jolts and vibrations. The Kinect also does not work well outdoors, especially in direct sunlight (which interferes with the projected IR pattern).

The Kinect is accessed through an open-source API called OpenNI (Open Natural Interraction). However, the actual skeleton tracking is done by a closed-source binary (NITE, made by PrimeSense.) NITE provides few options for configuration, so it was not possible to probe the inner workings of the drivers and provide fixes at that level. Higher-level software workarounds had to be employed.

The Kinect has several disadvantages that had to be overcome, largely due to the closed-source nature of the skeleton-tracking software.

# CALIBRATION

By default, whenever OpenNI detects a new user in its field of view it requires the user to stand in a calibration pose [PICTURE] enable an accurate measure of the user's limbs. This calibration step takes several seconds and requires the target to be still.

When the Kinect is on a moving base, occasionally the target will be lost due to relative motion or jolts (as discussed later). Upon target reacquisition, recalibration is frequently necessary. Recalibration would require both Harlie and the target to come to a halt, which is unacceptable given the goal of smoothly following the target. Luckily, through somewhat of a hack, OpenNI can be instructed to save the calibration of the first detected user, and for all subsequent users to use the saved calibration.

Skipping the calibration step comes at a cost. The distinctive pose required for calibration reduces the possibility of the robot following the wrong user, because it is highly unlikely that a bystander would make the pose. Without the calibration step, Harlie no longer has an easy way of telling which user to track. Furthermore, when on a moving base, the Kinect tends to classify some chairs as users. These chairs would never pass the calibration step, although without calibration they appear as spurious measurements.

Also an issue with OpenNI, the default behavior of the software is to track the entire human body (head, arms, torso, and legs). Full-body tracking is desirable for the Kinect’s intended application as a game controller, although Harlie's Kinect is mounted in such a way that users’ legs are often obscured (INSERT MECHANICAL DRAWING OF KINECT'S FOV). Luckily, OpenNI can be instructed to ignore legs and just track the target's upper torso , head, and arms. This results in an additional tradeoff: without the shape cues that legs provide, the tracking software loses an important characteristic that can discriminate people from inanimate objects.

# DISCRIMINTATION BETWEEN USERS

A major issue with the Kinect is the lack of built-in facilities for discriminating between different users. While in theory the Kinect has the potential to store color and texture information to recognize individuals, in practice, once OpenNI calibrates on a user, no information is stored other than limb measurements.

If a user exits the scene, there is no guarantee that when the user is re-detected that user will be assigned the same ID. The same is true if a target is momentarily lost due to a sudden bump or relative motion.

The Kinect relies on continuity between frames to maintain a lock on a target, which is perfectly fine for its intended application as a game controller where players never leave the field of view and the Kinect is stationary so the target lock is rarely broken.

However, for my application with a moving base, frequent dropouts are a fact of life and must be dealt with. My solution, as explained later, is to use the Kinect as one of several inputs to a Kalman filter that tracks the overall hypothesized location of a person (to be discussed in a later section.)

# LIMITED FIELD OF VIEW

The Kinect has a field of view of 57 degrees. While this is sufficient for tracking a target with limited freedom from a fixed vantage point, it shows weaknesses for moving targets.

When using the Kinect as the sole source of observation, Harlie must constantly face the user (within ±29 degrees) or lose the target. This puts severe constraints on the ability to maneuver and plan paths while maintaining contact with the target.

Even a task such as following a target down a straignt hall can be problematic. If an obstacle appears between the user and the robot, the robot must navigate around the obstacle. As part of the obstacle avoidance, the robot will likely rotate far enough that the user leaves the Kinect's field of view, leading to a target loss. When the robot once again faces the user, it will have to re-acquire the user, leading to delay. (INSERT IMAGE HERE OF ROBOT AVOIDING OBSTACLE, INCLUDING TANGENT ANGLE DEVIATION FROM STRAIGHT PATH)

The situation becomes even worse if the user doubles back behind the robot. In tight spaces such as hallways, the user will necessarily come close to Harlie when moving behind it. The Kinect’s depth camera breaks down when targets are closer than 2-2.5 feet away. Thus, Harlie has a blind spot when relying on the Kinect alone, and has trouble tracking targets that are very close. In a hallway scenario, this can result in Harlie being stuck pointing at close range to a wall, within the blind-spot range. (IMAGE OF DESCRIBED SCENARIO WITH TWO-FOOT BLIND SPOT)

# MOVING BASE PROBLEM

The Kinect was designed to track skeletons from a fixed vantage point (in front of a television.)

The Kinect was not meant to be mounted on a moving base. I performed some tests to characterize how well the Kinect can track moving targets from a moving vantage point such as Harlie's back. First, the robot was rotated back and forth through 1 radian of angle (approximately the Kinect's FOV) with a sinusoidal velocity profile. Second, step commands were given in angular velocity and the affect on tracking was observed. Target acquisition and tracking was tested up to 0.8 radians/second in both cases.

When the Kinect is still, its performance was best. The Kinect can detect users rapidly moving through the scene, and it can easily deal with partial occlusion. The Kinect only lost a lock when a target moves very quickly, or exits and reenters the scene. The Kinect can be confused if two users come close together, not being able to tell users apart by means other than their spatial positions.

As expected, the Kinect's performance gradually degrades with the speed of rotation. With a peak or step inputs below 0.3 radians/sec (17 degrees/sec), the performance is almost identical to the case of standing still. The Kinect is still able to robustly track targets through its field of view without many drops.

As the maximum speed increases, performance starts to degrade. Around 0.5 radians/sec, the target will occasionally occasionally be dropped. Usually the Kinect will reacquire it right away, resulting as a flickering effect as the Kinect struggles to keep a lock. The incidence of flickering increases with speed, and well as the chance that the Kinect will lose a target and not reestablish it. Target loss was especially noticable when the Kinect is jolted or given a sharp step command in velocity.

The quality of target tracking is also dependent on the environment. The Kinect is able to track closer users more reliably, likely because they have a greater number of constituent pixels. Occluded users are more dificult to track, especially if the occluding object is close by [INSERT PICTURE OF CHAIR BEING INTERPRETED AS BODY PART].

All of these effects are dependent on speed. Even so, at the maximum tested speed of 0.8 radian/second, the Kinect performed remarkably well given that it is operating outside of its design parameters. Although it frequently loses a lock, it is usually able to reacquire.

It is much more difficult for the Kinect to acquire a target when motion is involved (either a moving target or a moving camera). Frequently, the robot must come to a halt before the target can be reacquired.

Nevertheless, the problems are significant enough to warrant addressing.

Relative motion is a more significant problem than absolute motion. If the target keeps pace with the robot's rotation to remain in the center of the Kinect's FOV, tracking is very accurate.

Targets further away from the Kinect

I hypothesize that the Kinect uses background subtraction and tracks users frame-to-frame. Tracking is a more difficult problem when the base is moving. If the