Odometry Correction for Humanoid Robots Using Optical Sensors

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Abstract. Odometry measurement is an important concept to update localization information, but is prone to error propagation. Still the method is widely applied to wheeled mobile robots since their motion is quite robust to random error such as slipping. While the concept of odometry can also be applied to humanoid robots the dynamically stable walking generation reinforces sliding motions resulting in unpredictable errors. Therefore this paper proposes a novel approach to measure these sliding errors with the help of optical sensors to either correct the odometry update or perform suitable actions to counteract the error.

1 Introduction

With the development of more capable robotics hardware autonomous robots become able to solve more complex tasks. This opens up new possible application areas such as rescue operations or service activities. To fulfill tasks in these areas of application, robots must be capable of navigating in environments designed for humans or rough terrain. Those environments are particularly challenging for the movement of conventional wheeled autonomous robots. Normal stairs or small objects lying on the floor become insurmountable barriers. For these reasons modern robotic design tries to mimic human appearance with respect to body design, capability of gestures and facial expressions [1]. As a consequence humanoid robots are one of the major topics of robotics research and are believed to have high potential in future applications.

To solve given tasks a mobile robot is required to navigate in known or unknown environments. This kind of goal orientated movement requires some methods of localization to apply path planning algorithms [2]. The planning algorithm needs a global initial position as an input which can be calculated with the help of a wide range of external sensors, such as laser range finders or cameras. In addition the algorithm needs localization updates during the motion execution to supervise the executed path. Thisf information can either be global or differential local updates relative to the last known robot position. Filter algorithms, such as Kalman [2], can be applied to update the current position using the initial position and the differential sensor update. While a differential position update can be derived form every form of global sensor information most global

J. Ruiz-del-Solar, E. Chown, and P.G. Ploeger (Eds.): RoboCup 2010, LNAI 6556, pp. 48–59, 2011.

localization methods are not accurate enough to be useful to calculate small differential updates. Therefore a common concept is to update the current position with the help of movement information. Such motion can either be theoretically calculated by using the actuator input or by measuring actuator output with the help of internal sensors. This concept the is called *odometry*.

The next section gives an overview of research on odometry and related work with special focus on possible odometry update errors. In the following sections a concept is proposed to measure such errors and is tested in several experimental setups.

2 Odometry

Using actuator movement to estimate the current position is a common concept in mobile robotics. The position change can either be calculated using the given motor commands or measured with the help of sensors. While in an ideal world both methods would yield the same results they differ in reality due to deviations in motion execution. Thus utilizing the measured motion update is more error-proof and hence preferable. To update the current position sensors can measure either the current speed of the robot or the executed actuator motion. While both principle have been successfully applied to wheeled robots in the past, they can not be adapted to humanoid robots easily.

Acceleration sensors allow the tracking of the current speed of the robot. As long as the robot has no need to move its body to achieve postural stability, which is true when utilizing at least three wheels, the body can be kept in an upright position. Hence for wheeled robots with a rigidly fixed connection of wheels all measured acceleration relates to a position change. Movement of a humanoid robot is different in contrast to a rolling robot. The nature of legged walking requires some movement of actuators that does not result in a direct position change of the robot. While slow movement, which satisfies the static stability criterion, ensures a rather stable position of the upper body, fast movement, which requires dynamic stability, results a movement of the robots *Center of Mass* (CoM) leading to a periodic motion of the upper body. While in theory integration over all acceleration changes would result in the change of position, this would require the knowledge of the body orientation in space. Since the orientation of the body can only be estimated and walking movements results in a rather swaying movement, the odometry estimation with help of an accelerometer is not practical for humanoid robots.

The second principle of odometry measurement is to update the position with the help of actuator movements. Since rolling robots are supposed to have ground contact with all wheels at all the time every actuator movement relates directly to a position change of the robot. With the help of wheel encoders calculating the resulting movement is therefore straight forward [3] if the kinematic structure of the wheel positions is known. The walking motion of a two-legged robot requires to periodically lift one leg, resulting in a change of double- and single-support phase [3]. Hence not all motion during the single support phase will result directly in a change of position, but will alter the support polygon of the robot. Only a shift of the CoM relative to the support polygon leads to a position update of the robot. Thus the combination of the CoM motion relative to the support polygon and expanding the support polygon whenever a single support phase merges into a double support phase results in the movement of the robot during a step. With most legged robots utilizing servo motors which allow to get a position feedback these sensors can thereby be used to calculate the odometry update during the walk resulting in a practical way to measure the relative movement of a humanoid robot.

3 Odometry Error

Due to the incremental nature of odometry this localization method is susceptible to error propagation. A false motion update influences the starting position of the following updates and therefore sums up over time. Errors in odometry measurements can be divided in two types of errors. The first being systematical measurement error while the second arises of actuator movement not resulting in a position update of the robot. Systematical measurement errors can be eliminated by correction or calibration of the sensor information. But predicting when errors of the second class will occur during motion execution is not easily done. Thus they can only be classified as statistical errors. Since every odometry error effects the following prediction update even non-systematical errors can result in a big position estimation error over time. This is especially true for errors in orientation, resulting from incorrectly measured rotational motion, since these sum up to errors in x- and y-position over time [4]. The wheels of a rolling robot are designed to maximize ground friction in order to move. Thus a wheeled robot seldom violates the sliding constraint reducing the impact of the second error class. With good calibration odometry updates for wheeled robots can therefore be seen as quite accurate resulting in a good practical way to update the localization while moving.

While legged robots also try to achieve enough friction during the ground contract to move the robot the impact of the second class of errors becomes more serve. If the friction of the foot is too high slight deviations in putting the foot on the ground can cause a jolt resulting in a fall of the robot. Humanoid robots tend to use the concept of dynamical stability to generate fast walking motions [5]. Thus the material of the robot sole is chosen to be able to slide on the ground when not the complete weight of the robot is supported by this foot. The concept is based on keeping the *Zero Moment Point* (ZMP), which is not taking into account the moments around the vertical axis, inside the support polygon. With faster walking speeds this requires high acceleration of the actuators resulting in forces acting on the robot. When these forces exceed the force the ground friction can hold this results in a sliding motion of the robot. A good illustration is the movement of the swinging foot during the single support phase. The acceleration needed to place the foot on the desired ground position results in a torsional moment around the support foot rotating the robot around the vertical axis. Since the amount of rotational movement depends on many factors such as the local ground characteristics and the current robot pose the rotation can neither be calculated or predicted and thereby leads to odometry errors of the second class resulting in a deviation in position over a couple of steps. Since the sensor data of both accelerometer and gyroscope are prone to noise due to the swaying walking movement the robot has no sensors capable of measuring this position update. Therefore this paper proposes a novel approach to measure the slipping movement of a humanoid robot described in the following section.

4 Measurement of Odometry Errors

The described motion errors have a great influence on odometry measurement of biped robots. Therefore a way to measure these errors would greatly improve the quality of odometry updates. Since none of the internal sensors is capable of measuring the deviation resulting of the sliding movement the need to apply new sensors arises. The motion that should be measured is the sliding movement of the support foot. This foot is supposed to have contact to the ground during the complete single support phase and should be lifted after the following double support phase. During this single support phase every movement of this foot relative to the floor directly results in a position change of the robot.

Sensors used for optical mice are designed to measure motion updates relative to the ground. The sensor is tracking the position update of the sliding motion while the mouse bottom side has flat contact to the ground. In the past experiments with optical sensors have proven them to be able to support the update of odometry information of rolling mobile robots [6], but since the optical mouse is designed to have ground contact such a sensor either limits the ground clearance of the robot or requires an adapted optical lens system. Modern laser sensors are powerful enough to track both high acceleration and speed on most surfaces. New technologies like Microsoft's *BlueTrack*[1] and Logitech's *DarkField Laser Tracking*[2] sensor are even capable of tracking movement on uneven and reflecting surfaces such as glass. Since the ZMP, and therefore the *Center of Pressure* (CoP) [5], is supposed to be beneath the standing foot during the single support phase, the foot will be pressed flat to the ground. Hence an optical sensor positioned under the foot surface should be able to measure the motion of the foot during the support phase, if the ground is planar.

A mouse sensor provides a motion update in x- and y-direction by incrementally adding up *counts*. Therefore with a given start position $S(x, y)$ and a measured end position $S'(x', y')$ it cannot be distinguished if the update resulted from a pure translation, a pure rotation or a combination of both. Since a single mouse sensor would not be sufficient to also track rotation the need to combine two sensors arises [6].

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[1] `http://www.microsoft.com/hardware/mouseandkeyboard/tracklanding.mspx`

[2] `http://www.logitech.com/images/pdf/briefs/Logitech_Darkfield_Innovation_Brief_2009.pdf`

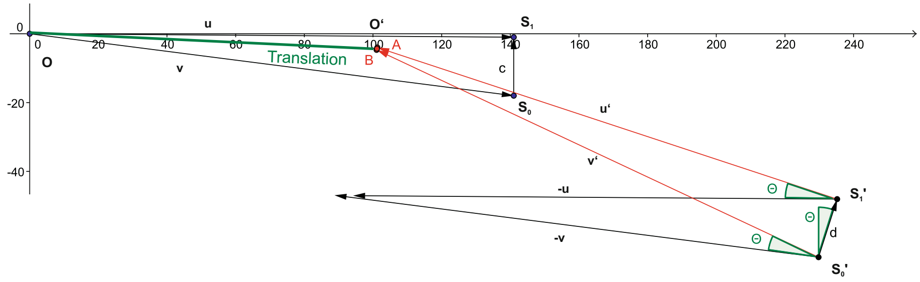

Fig. 1. Foot movement(translation = 100 *mm*, rotation = 20 *deg*)

Figure 1 displays example sensor positions $S_0(x_0, y_0)$ and $S_1(x_1, y_1)$ before and after a motion that includes translation and rotation. Since the foot is assumed to be flat on the ground, the z-coordinate is neglected. The position of the sensors in reference to center of the foot coordinate system, labeled in figure 1 as O, fixed and therefore the positions in the robot coordinate system can be calculated by the help of inverse kinematics. The updated sensor positions $S'_0(x'_0, y'_0)$ and $S'_1(x'_1, y'_1)$ after the motion in the old foot coordinate system can be derived by adding the measured sensor motion $\mathit{\Delta} S_0$ and $\mathit{\Delta} S_1$.

With the new sensor positions the foot rotation can be deduced by calculating the angle θ between the vectors $\boldsymbol{c}$ and $\boldsymbol{d}$.

$$\mathit{\Theta} = \arccos\left(\frac{\boldsymbol{c} \cdot \boldsymbol{d}}{|\boldsymbol{c}||\boldsymbol{d}|}\right) \tag{1}$$

The rotation sign results from calculating the cross product of $\boldsymbol{c}$ and $\boldsymbol{d}$.

$$\boldsymbol{c} \times \boldsymbol{d} = \begin{pmatrix} c_2 d_3 - c_3 d_2 \\ c_3 d_1 - c_1 d_3 \\ c_1 d_2 - c_2 d_1 \end{pmatrix} \tag{2}$$

The vectors $\boldsymbol{u}$ and $\boldsymbol{v}$ are the given position of the Sensors S_0 and S_1 in the foot base coordinate system. Transforming these with the help of the rotation matrix for the calculated rotation $\mathit{\Theta}$ results in the vectors $\boldsymbol{u}'$ and $\boldsymbol{v}'$.

$$\boldsymbol{u'} = \begin{pmatrix} cos\mathit{\Theta} & -sin\mathit{\Theta} \\ sin\mathit{\Theta} & cos\mathit{\Theta} \end{pmatrix} \boldsymbol{u} \tag{3}$$

$$\boldsymbol{v'} = \begin{pmatrix} cos\mathit{\Theta} & -sin\mathit{\Theta} \\ sin\mathit{\Theta} & cos\mathit{\Theta} \end{pmatrix} \boldsymbol{v} \tag{4}$$

Subtracting these vectors from the new sensor positions S'_0 and S'_1, respectively, results in the new center of the foot coordinate system $\boldsymbol{O'}$

$$\boldsymbol{S'_0} - \boldsymbol{v'} = \boldsymbol{O'_v} \tag{5}$$

$$\boldsymbol{S'_1} - \boldsymbol{u'} = \boldsymbol{O'_u} \tag{6}$$

The resulting $\boldsymbol{O'_v}$ and $\boldsymbol{O'_u}$ are theoretically identical. In reality both will differ due to errors in sensor output. The new center of the foot coordinate system will therefore be arithmetically averaged from both sensors.

$$\boldsymbol{O'} = \frac{\boldsymbol{O'_u} + \boldsymbol{O'_v}}{2} \tag{7}$$

The foot translation $\boldsymbol{T}$ is calculated by subtracting the old from the new foot coordinate system center.

$$\boldsymbol{T} = \boldsymbol{O'} - \boldsymbol{O} \tag{8}$$

Combining the rotation θ and translation $\boldsymbol{T}$ transforms the old foot pose p in the new foot pose p'.

$$p' = R(\theta) \cdot p + T \tag{9}$$

5 Evaluation

To evaluate the concept presented in this paper, experiments were conducted using a robot of the type *Nao* designed and build by Aldebaran Robotics[3]. The robot has no optical sensors integrated in the feet and therefore has to be equipped with such a setup to perform the experiment. From the wide variety of optical sensors the ADNS-5030 produced by *Avago* is chosen, being specially designed for the use in wireless optical mice. Thus the rather low energy intake of 15.2 mA making it ideal for usage in a mobile system without stressing the power supply. The sensor has a resolution of 2000 *Dots per Inch* (DPI) which is high enough to measure even small motions. Initial performance tests have been done with the help of a robotic manipulator. The results of the experiment prove the sensor to perform well on different surfaces, such as paper, carpet, concrete, linoleum and laminate flooring. The measurement accuracy is not affected by speeds up to 1.1 m/s and accelerations up to 0.9 m/s. All used sensors are individually calibrated by the experimental outcome of these tests as a reference to match the measured counts to the moved distance. When lifted above 0.3 mm off the ground the sensor did not measure any motion while moving, assuring that the sensor of the swinging foot will measure any motion. In this situation this is desirable since the measurement would otherwise incorrectly affect the motion update. Due to the tests classifying the sensor performance to be adequate and the fact that the optical lens system of a laser sensor is much larger and therefore more complicated to integrate in a humanoid robot foot, the LED sensor ADNS-5030 is chosen over more powerful optical laser sensors.

The ADNS-5030 is utilized in a custom designed board. Since the robot *Nao* is not self build and its internal interface and layout is not published the sensor board can not be integrated in the foot and has therefore to be attached externally. This is done with the help of a kind of overshoe, attaching the board directly in front of the foot (see figure 2). The material of the shoe is chosen

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[3] http://www.aldebaran-robotics.com/

to reflect characteristics of the sole of *Nao*. The information collected by the sensors is transmitted to *Nao* with a wireless connections based on the *ZigBee*[4] standard connected to the USB port making a transmission possible within the 20 *ms* time frame given by the used framework.

5.1 Odometry Sensor Setup

With reference to section 4 it becomes obvious that the position of the sensors influence the quality of the measured motion. Even if being highly accurate under ideal circumstances the sensor output will be flawed when used on none ideal surfaces by adding random noise to the measurement.

If the robot is turning it is logically supposed to rotate around the current CoP being the point which has currently the highest static friction. To ensure stability the CoP is preferably positioned in the middle of the foot. Hence positioning the sensors distant to the center will result in a bigger distance traveled by the sensor lessening the absolute influence of noise. But as can be seen in equation 1 the measured rotation is highly influenced by vector $\boldsymbol{c}$ which relates directly to the position of the sensors relative to each other. Therefore a first experiment will evaluate two different sensor setups. The first configuration, from here on denoted as *Configuration 1*, can be seen in figure 2(b) on the left. The two sensors are positioned within the same board placing them 17 *mm* apart from each other. In contrast an additional sensor board is attached to the heel of the robot, seen in figure 2(b) as *Configuration 2* on the right, resulting in a distance of 232 *mm*.

To prove the theoretical concept proposed in section 4 and to evaluate the influence sensor noise in respect to different sensor positions the robot is equipped with both sensor configurations and a combined translation and rotation is performed. The sliding motion is executed manually to ensure ground contact for both sensor setups during the complete motion. Three separate experiments are performed repeatedly, figures 3, 4 and 5 showing chosen representative results. Experiment 1 and 2 demonstrate motion being purely rotational respectively translational. Figure 3 illustrates clearly the impact of the sensor distances on the measured rotation. While the measured results of *Configuration 2* match the real rotation, the impact of the sensor noise on *Configuration 1* due to the short distance becomes obvious. The results of the second experiment (see figure 4) demonstrate the same tendency. While the translation is not directly influenced by the distance between the sensors the reason for the second configuration performing significantly better becomes clear when recapitulating the calculations demonstrated in section 4. To calculate the translation, the foot rotation has to be calculated before. Therefore the rotation noise influences the translation even when no rotation took place in reality.

The third experiment combines both motions, a rotation and a translation in x direction, to one sliding movement. The results of the rotation calculations are demonstrated in figure 5(a), the following translation calculation can be found

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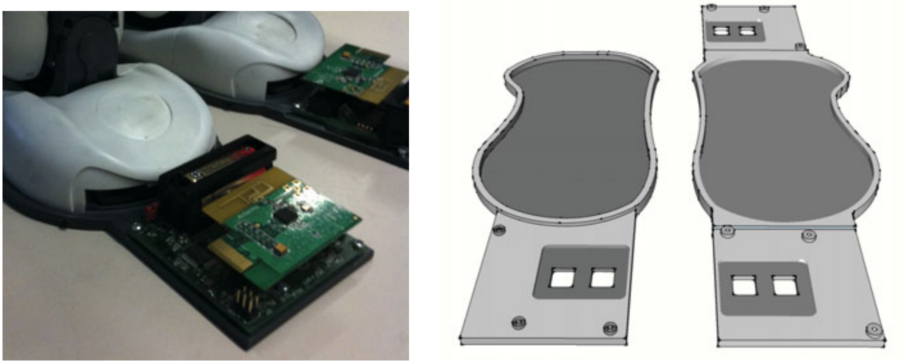
[4] IEEE 802.15.4.



(a) Sensor board

(b) Schematic view. Configuration 1 on the left, Configuration 2 on the right.

Fig. 2. Sensor placement

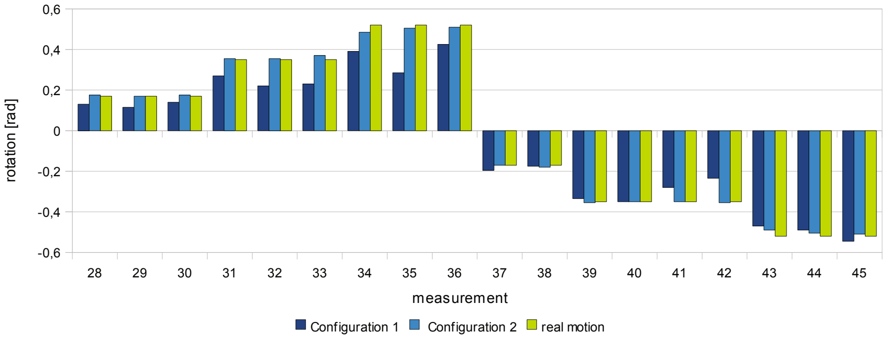


Fig. 3. Experiment 1 - Manual rotation

in figure 5(b). The outcome of the rotation measurement again puts the second configuration ahead of the first, but with a higher variation due to the noise interaction with the translation motion. As a result the translation also yields inferior results but still measures the motion to a satisfying accuracy.

5.2 Walking

Since the first experiment proves *Configuration 2* to be superior all following experiments only utilize this sensor setup. The described experiments support the conclusion that the sensor setup allows to measure the slipping motion, and thereby the odometry error, during a walk. Thus the last experiment, described in this paper, demonstrates the results of the sensor measurement of an autonomous walk. While the additional weight of the sensor boards influences the walking of *Nao* the parameters of the utilized walking engine [7] are adapted to ensure a stable motion.

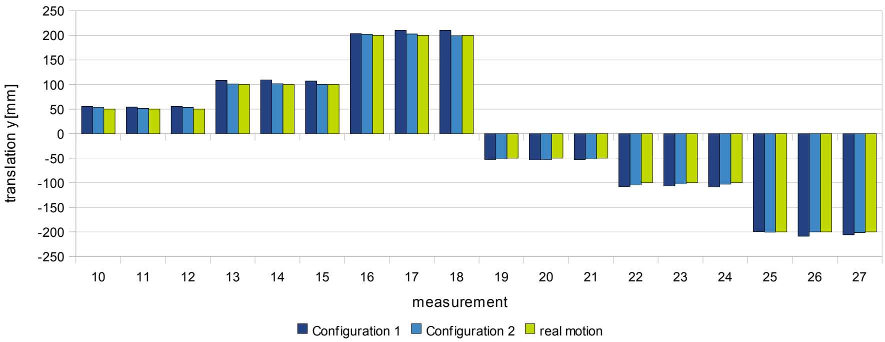
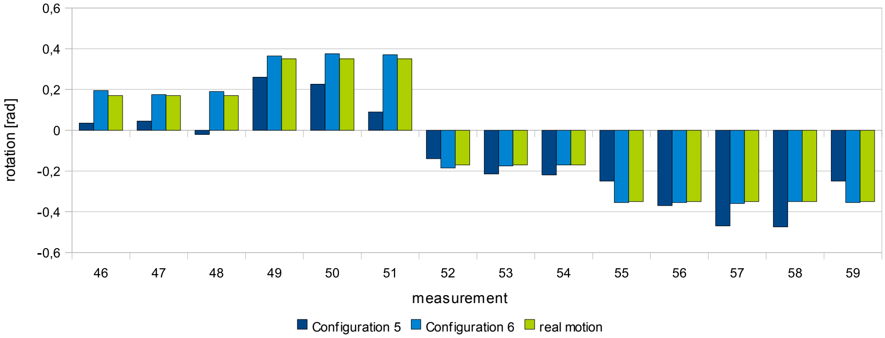
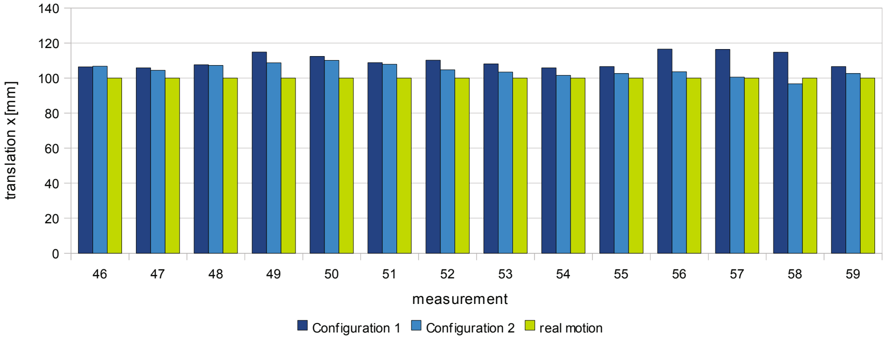


Fig. 4. Experiment 2 - Translation in y-direction



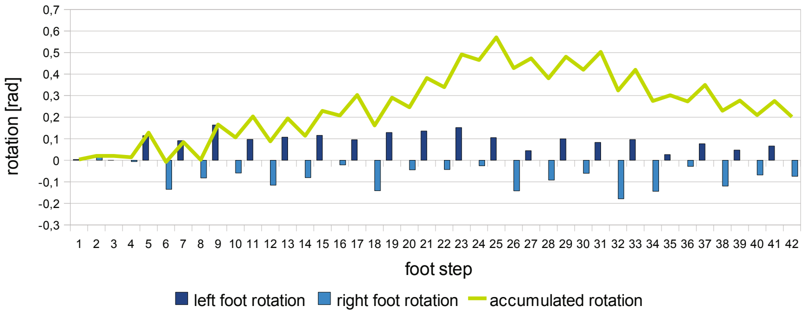
(a) Rotation measurement



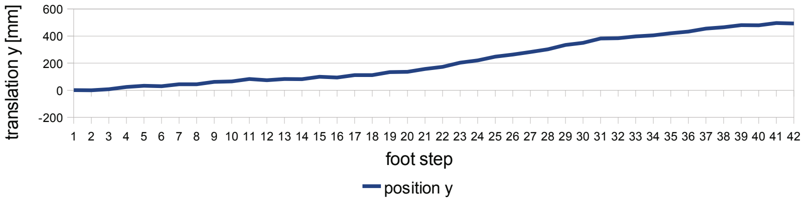
(b) Translation measurement in x-direction)

Fig. 5. Experiment 3 - Manual combined motion

The Measurement set number 86 of figure 7 is illustrated as a more detailed example walk in figure 6. As expected a rotation of the support foot can be observed during every single support phase, caused by the movement of the



(a) Step rotation

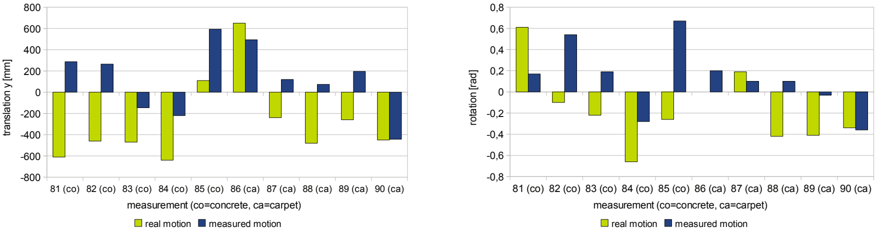


(b) Accumulated y-translation error

Fig. 6. Example walk in x direction

swinging leg. The direction of the rotation depends on which leg is swinging, but the amount of rotation differs on every step. Therefore the accumulated rotation increases in positive direction causing a deviation of the walk in y-direction which cannot be observed by the odometry. The measured deviation of 49.2 cm does not match the observed real deviation of 65.0 cm but clearly helps to correct the odometry update.

Figure 7 illustrates a representative sample measurement of the same walking experiment on different floor types. Most interesting is the analysis of the resulting y-direction error in figure 7(a). Since a validation of each step rotation is not possible due the lack of a reference measurement, the resulting deviation in y-direction over time of the walk is the best proof of the rotation measurement quality. As figure 7(a) illustrates every walking test results in of y-deviation over the executed time proofing that the influence of the observed rotation is significant. The results of the sensor measurement, however, show a wide distribution with some results even measuring a drift in the opposite direction. This result is contrary to these of the previous experiments and therefore requires discussion. Due to the incremental nature of the experiment the source and influence of a measurement error cannot be derived from the outcome. A small error on the first rotation measurement can lead to a large drift over the course of the walk, while the same error made during the last step would have no influence at all. But the observation of the experiment allows some conclusions that explain the variance of results.



(a) Error y-translation (b) Error rotation

Fig. 7. Experiment 4 - Walking in positive x-direction with speed 100 mm/s

First of all as can be seen in figure 6(a) the occurring rotation during the walk can be located around 0.1 *rad*. Even though Experiment 1 has proven that the measured motion update for this dimension is satisfactory under ideal circumstances such small updates make the measurement more susceptible to sensor noise. The movement generated by the walking engine results in a much bumpier motion than the manual motion, resulting in less ideal conditions. Due to the utilized closed loop sensor control a countermeasure to assure stability can even result in a rocking motion lifting a part of the foot off the ground shifting the CoP and thereby the rotation center. This can result in one sensor being lifted higher off the ground than its height-tolerance resulting in a false rotation measurement. Since the rocking motion is worse when accelerating the robot from a standing position this explains part of the deviation.

6 Conclusion

The experiments prove that updating odometry of humanoid robots with information of optical sensors is a big advantage in principle. The sensors can measure motions unobservable by the conventional methods to measure odometry allowing an error correction of the motion update. This helps to improve especially local localization e.g. when trying to approach an object. An online compensation of the error by adaptation of the walking patten could not be tested due to the variation of sensor output during autonomous walking.

The results of the experiments prove the importance of suitable sensor placement with placing the two sensors further apart being more favorable. But the observations also suggest that it is more beneficial to place the sensors closer to the CoP by moving them nearer to the center of the foot. This would result in less lifting of the sensor during the rocking walking motion and thereby would improve the measurement. Unfortunately this influence could not be verified experimentally due to the nature of the experimental platform allowing no sensor placement inside of the feet. The experiments were conducted with the help of the sensor ADNS-5030. It has been chosen due to its benefits for the application in smaller mobile robots, such as the utilized robot *Nao*. The walking experiment however revealed some flaws of this choice. The nature of two legged dynamic walking requires sensors with a larger height and overall better noise tolerance. Sensors for modern gaming mice feature both attributes, but especially recent development of new technologies such as *BlueTrack* and *DarkField Laser Tracking* are promising. They are believed to yield much better results since they claim to work on virtually any surface. But since the sensors are not commercially available for developers testing these sensors has to be done in future work.

References

1. Kanda, T., Ishiguro, H., Imai, M., Ono, T.: Development and evaluation of interactive humanoid robots. Proceedings of the IEEE 92(11), 1839–1850 (2004)
2. Thrun, S., Burgard, W., Fox, D.: Probabilistic Robotics. MIT Press, Cambridge (2005)
3. Siegwart, R., Nourbakhsh, I.R.: Introduction to Autonomous Mobile Robots (Intelligent Robotics and Autonomous Agents). MIT Press, Cambridge (2004)
4. Borenstein, J., Feng, L., Borenstein, C.J.: Measurement and correction of systematic odometry errors in mobile robots. IEEE Transactions on Robotics and Automation 12, 869–880 (1996)
5. Vukobratovic, M., Borovac, B.: Zero-moment point – Thirty five years of its life. International Journal of Humanoid Robotics 1(1), 157–173 (2004)
6. Bonarini, A., Matteucci, M., Restelli, M.: Automatic error detection and reduction for an odometric sensor based on two optical mice. In: ICRA, pp. 1675–1680 (2005)
7. Czarnetzki, S., Kerner, S., Urbann, O.: Observer-based dynamic walking control for biped robots. Robotics and Autonomous Systems 57(8), 839–845 (2009); Humanoid Soccer Robots