Practical Issues in Utilizing Intelligent Motion Control Layer in UGV-type Robots

Maido Hiiemaa, Mart Tamre
Tallinn University of Technology, Department of Mechatronics
maito@staff.ttu.ee

Abstract
Useful features and limitations of Intelligent Motion Control Layer (IMCL) have been brought out, when utilized in the remotely controlled UGV. When driving on a flat terrain and avoiding any obstacles, disturbance components can effectively be detected and compensated by IMCL using real-time wheel encoder data. Hard and bumpy terrain is different and requires at least one additional 3-axis accelerometer to be integrated into payload area to collect data about acceleration and jerk peaks. Experiments made on our UGV show that limiting UGV driving speed is helpful but does not entirely solve the problem.

Keywords
Intelligent motion control, control hardware design, disturbance rejection, motion prediction, driving aids

Introduction
Using UGV-type of robot for transporting delicate equipment is applicable when payload area (and payload) does not suffer from intensive jerk and acceleration peaks. In practice, these peaks mostly occur when either running into obstacles or driving too fast on a hard and bumpy terrain [1]. Several driving aids should be developed for UGV operator to avoid undesired driving results like damaged cargo or damaged UGV.

Original IMCL was simulated and evaluated using long feedback delay, reduced encoder resolution and extremely rough terrain changes to bring out more and less useful features of this concept [2,3]. It was proven, that extreme terrain changes may cause jerk and acceleration peaks that are undesired in case of transportation. In real UGV hardware the data delays can be reduced several hundred times and wheel encoder resolution can be increased more than 30 times. This still cannot effectively constrain acceleration peaks on any kind of terrain. Most problematic situations occur when wheels often drop from rough edges while driving on hard and bumpy terrain. In such conditions wheel encoders alone may not capture the payload motion adequately.

There are only few UGV stances where acceleration peaks could be detected based on leg encoders for torsion spring torque feedback. Using 3-axis accelerometer on top of the UGV is therefore proposed as a solution to monitor payload area jerk and acceleration peaks. In case the magnitude and density of the peaks exceed predefined levels, UGV velocity must be significantly reduced to protect the payload. UGV operator should always visually evaluate terrain conditions to avoid wheels from slipping and dropping off the rough edges. IMCL needs only minor modifications to be able to continuously predict the closest possible full stop point assuming that terrain conditions remain the same and predefined acceleration and jerk levels would not be exceeded. Visualizing this point on operator screen could be useful mostly driving on flat terrain.

Control Hardware
There are several hardware design considerations to be taken into account when planning IMCL to be utilized on a UGV control system. Although IMCL was designed to overcome rather long feedback delays, better performance can be achieved when all data delays, as well as time-step duration, are designed short. UGV that has been developed in TUT Dept. of Mechatronics [1] has 4 legs, each with its own wheel and torsion spring (Figure 1).

![UGV without payload](image)
12 encoders are being used for UGV wheel and leg feedback. Four BLDC motors give UGV its ability to drive and turn (wheel servos) and four BLDC motors change its centre of balance and clearance (leg servos).

**Wheel Servo Amplifiers**

Current version of UGV uses speed command input servo amplifiers, which already has built-in disturbance compensation. This design can therefore only partly benefit from IMCL functionality. Torque commands (without disturbance compensation components) must be converted to velocity commands and sent to the servo amplifiers.

To use IMCL, as it was originally designed, simple current-loop type of servo amplifiers should be used. Motion predictions can be effectively done when torques of all wheels and disturbance components of the terrain are known [2]. Disturbance components can be calculated by analysis of most recent UGV kinetic energy change, recent wheel torque data and terrain ascent angle. Wheel torque is a function of motor current (acquired by current sense signal) and velocity (acquired by wheel encoders). IMCL compensation parameters are added to torque command to implement disturbance rejection. Although IMCL output can be converted to describe required motor current level, actual motor current should be monitored using current sense signal provided by servo amplifier or external current sensing circuitry.

In original IMCL simulation force command (converted from "acceleration command" containing compensation part) was used as output, without converting it to wheel torques and back to force so the Simulink model could be a bit more compact. Servo amplifiers and related problems were not simulated.

**Digital Interfacing**

The IMCL algorithms have been written mostly in Matlab and can be easily translated into C-language to integrate it into on board microcontroller software, which already has drivers for all devices on board. Data acquisition involves many encoders (wheel and leg related). All encoders are I\(^2\)C compatible. Due to lengthy data lines (>1 m), buffers enabling higher (up to 15V) signal levels to be used. The I\(^2\)C clock frequency can be up to 400kHz, which is sufficient to capture all encoder positions more than 1000 times per second. The actual maximum acquisition frequency is about half of that because servo amplifier commands need to be updated at the same rate as encoders. Test results show that time-step of 0.01 seconds (refresh rate of 100Hz) is more than satisfactory. Digital gyroscope/accelerometer is interfaced by UART giving all angular and acceleration data up to 100 times a second at 115.2 kBaud.

**Feedback from Leg**

Every UGV leg has built-in torsion suspension to mechanically protect leg worm gears in case of sudden impacts caused by running into obstacles. To measure leg position and torque in real-time, two separate encoders are needed. The first one measures angle between worm transmission output and UGV chassis. The second encoder measures angle between worm transmission output and leg. This angle can be translated to leg torque using simple formula.

\[ M = 1,7229\varphi - 10,609\varphi + 98,4 \]

Having torque information for every leg can be (in some situations) used when changing UGV clearance or weight distribution. Currently this task is not automated but it can be performed remotely based on leg torque data, which is available on operator screen, and personal experience.

To calculate angle between UGV chassis and leg, two encoder readings must be added. Currently all leg related encoders have resolution of 4096 positions per revolution.

**Feedback from Wheel**

Wheel encoders are providing essential motion feedback in IMCL. To keep approximation noise low, it is favourable to use high-resolution encoders. Excellent results can be achieved using Integrated Hall IC for Linear and Off-Axis Rotary Motion Detection along with circular magnet strips from austriamicrosystems AG.

![Figure 1. Wheel Encoder](5)

The AS5311 resolution is below 0.5\(\mu\)m. It is a system-on-chip, combining integrated Hall elements, analogue front end and digital signal processing on a single chip, packaged in a small 20-pin TSSOP package. A multi-pole magnetic strip or ring with a pole length of 1.0mm is required to sense the rotational or linear motion [5]. Using ring diameter 83.4 mm gives total 131072 positions per revolution of a wheel. IMCL simulations using encoders with 1024 and 4096 positions per revolution gave noticeable approximation noise levels. When wheel resolution was raised to 131072 approximation noise was virtually nonexistent. Shortening time-step duration 10 times does not entirely eliminate the positive effect of decreased approximation noise.
**Velocity Tolerance**

Keeping UGV velocity strictly under control is not always necessary. In real-life applications, velocity deviation may be allowed, according to the nature of a mission. Wider velocity range contributes to the decrease of average current consumption. In case of UGV driving downhill, its control system does not need to apply any braking techniques before the upper velocity limit gets violated. Kinetic energy will be then efficiently dissipated as soon as terrain conditions change. Regenerative servo amplifiers can use kinetic energy of UGV to for charging batteries when dynamic braking is applied but this conversion is not as efficient.

**Terrain**

IMCL uses disturbance components detection and rejection as often as possible. In many cases UGV could record these components [2] and use the data for predicting the point of no return. Analysing battery discharge and simulating UGV driving the same path but in opposite direction may give useful early warning capabilities.

**Flat Terrain With Obstacles**

When terrain conditions are fair and usually change gradually, jerk and acceleration peaks will be kept under control by IMCL. Minor modifications of IMCL code enable automatic prediction of full-stop position in case of immediate stop command and non-changing terrain conditions. This point should be highlighted on operator screen (on top of video) or numerically. In case the operator ignores the warning data and may therefore collide with an object or if any moving object blocks UGV planned trajectory, dedicated rangefinder sensors should initiate the stopping procedure. Within one time-step a proper stopping scenario should be generated possibly with increased jerk and acceleration levels to avoid the collision. If following time-steps (with more recent data) predict differently, those levels may be adjusted accordingly. Because every mission may have different requirements and priorities, all levels (also emergency levels) must be revised carefully. Stopping procedure may be required after every failure of radio link. As soon as link is restored, stopping procedure may be halted and normal drive mode may be resumed causing only minor decrease of velocity when the link was down for a short period of time.

**Hard and Uneven Terrain**

Because terrain properties cannot be accurately predicted by IMCL and any disturbance compensation will be applied after it has slightly distorted UGV motion, acceleration and jerk peaks may occur on payload area (on top of the UGV) when driving too fast on an uneven and hard terrain. Wheel encoders do not always detect these peaks. Additional 3-axis accelerometer must be mounted on payload area to detect dangerous acceleration peaks, which may in short-term or long-term damage the payload. In TUT UGV, 3-axis accelerometer is embedded in 3-axis digital gyroscope, which alarms UGV operator about dangerous payload angles. Onboard computer keeps track of acceleration and jerk violations in terrain history file and lowers the maximum allowed velocity according to the recent event statistics. Every violation event will be excluded from terrain evaluation statistics one by one after driving a certain distance from the point of violation occurrence and maximum allowed velocity may be restored. TUT UGV legs can adapt to hard and uneven terrain to keep the payload not tilted too much. Leg positioning operations, however, must be performed cautiously and not while driving on a hard and uneven terrain.

**Conclusion**

IMCL original simulation parameters were chosen to get a better insight of the concept. Critical parameters like encoder resolution, and time-step duration were changed according to real hardware capabilities to give the concept new evaluation. Utilizing original IMCL with tuned parameters in UGV control system has several good features. Still real-life applications require data from additional sensors (accelerometers, digital gyroscope, leg torque feedback) and specific real-time analysis of the data along with automatic adaptation. Few IMCL-related driving aids were proposed for further development of the operator screen. Full set of necessary sensors and algorithms for TUT UGV is yet to be developed and tested for UGV semi-autonomous intelligent control.

**References**

1. Tallinn University of Technology, Department of Mechatronics, "Universal Ground Vehicle", Research project L523, 2005-2008.
3. Hiiemaa, M., Tamre, M,  *UGV-type Robot Motion Control Simulation*, Tallinn University of Technology, Department of Mechatronics, 4 p.
5. AS5311 High Resolution Magnetic Linear Encoder Preliminary Data Sheet, austriamicrosystems AG, 23 p.