Master Thesis

Validation of Machine-Learning-driven Real-Time 2D/3D Tracking (Texture Model Registration) in Radiotherapy

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Abstract

In almost all image guided medical interventions (IGMI) such as image guided surgery and image guided radiotherapy (IGRT) the spatial alignment of pre- and intra-interventional data plays a crucial role. For example in IGRT the planned patient setup must be verified right before as well as during beam delivery in order to guarantee an efficient treatment and to avoid adverse effects. Most of the IGMI require online (real-time) image information, acquired by projective images (e.g. radiographs) or slice-images (e.g. ultrasound). The current available projection-based 2D/3D registration approaches use optimization strategies that are potentially prone to local minima traps, usually have a data-dependent capture range and hardly meet critical real-time constraints.

In this work a novel framework for 2D/3D image registration (texture model registration, TMR), that utilizes supervised machine learning techniques, was implementated and quantitatively validated to overcome the limitations of current iterative methods. Based on a pre-interventional 3D image and geometry information a prediction rule is derived which is subsequently used for the real-time prediction of the spatial transformation of unseen intra-interventional 2D images. Two simple TMR methods were implemented and validated with a quantitative simulation of 120 experiments, based on realistic lateral and ventral IGRT scenarios on 15 different clinical computed tomography (CT) datasets and synthetic 2D images (DRRs). The implemented TMR pipelines are TMR-PCR, which involves principal component regression (PCR), and TMR-KPCR, which involves kernel PCR.

The results show that TMR is able to predict the translational parameters which are perpendicular to the projection direction ($\overline{\text{MSE}}$ 0.004-0.913 mm^2) and rotations within this plane ($\overline{\text{MSE}}$ 0.055-0.495 deg^2) with high accuracy. The prediction of the depth information was less accurate ($\overline{\text{MSE}}$ 2.409-13.211 mm^2), which was expected, because only a single image was used. The maximum values of the 95th mean target registration error (mTRE) percentile show that TMR produces very robust predictions under ideal conditions (1.156-2.556 mm), even at high initial mTREs. An increased $\overline{mTRE}$ (0.194-1.59 vs. 0.531-4.184 mm) can be observed at higher CT dataset resolutions. More details in the DRRs and the used non-robust statistical methods (sensitive to inflated variances and noisy pixels) lower the generalization performance. Higher transformation degrees of freedom (DOF) result in a less reliable registration (3.01-16.15 times higher mean $\overline{mTRE}$). This may mainly emerge from the increased dimensionality of the parameter space and can be overcome by more learning samples and better pre-processing operations. The head and neck experiments perform better than the prostate experiments. The lateral and ventral experiments perform similar.

The average intra-interventional registration rates of 43.84 and 64.92 Hz are convincing. TMR-PCR is not able to capture non-linearities in the transformations. TMR-KPCR with a polynomial kernel of degree 3 seems to be the method of choice. The vast majority of 2D/3D registrations in 60 experiments were successful (86.44-99.39%), where an end mTRE smaller 2 mm was defined as successful. The other experiments appeared to clearly suffer from the increased DOF (23.86-70,07%). However, the amount of 2D/3D registrations that have an larger or equal final mTRE than before the registration is very low (at most 0.1-0.31%).

TMR gives access to a wide range of algorithms and methods which are usually applied in a machine learning and computer vision context. In particular non-linear regression methods and manifold embedding methods.

Summing up, the validation results of the very basic setup of TMR are promising to be used in the field of automatic real-time 2D/3D image registration and in other areas of IGMI.

Zusammenfassung

In nahezu allen bildgestützten, medizinischen Eingriffen (IGMI), wie bildgestützte Chirurgie und bildgestützte Radiotherapie (IGRT), spielt die räumliche Registrierung von prä- und intra-interventionellen Daten eine wichtige Rolle. Beispielsweise muss bei IGRT die geplante Patientenposition kurz vor und während der Bestrahlung verifiziert werden um eine effiziente Behandlung zu garantieren und negative Auswirkungen zu vermeiden. Die meisten IGMI benötigen Bildinformation in Echtzeit, welche mit projektiven Bildern (z.B. Röntgen) oder Schichtbildern (z.B. Ultraschall) gewonnen wird. Die derzeitigen projektionsbasierten 2D/3D Registrierungsverfahren verwenden Optimierungsstrategien die anfällig sind für lokale Minima, eine datenabhängige Fangreichweite aufweisen und keine Echtzeitanforderungen erfüllen.

In dieser Arbeit wurde eine neuartige 2D/3D Registrierungsmethode (texture model registration, TMR), welche auf maschinellen Lernverfahren basiert, implementiert und quantitativ validiert um die Beschränkungen derzeitiger iterativer Verfahren zu bewältigen. Basierend auf prä-interventionellen 3D Bildern und Geometriedaten wurde eine Vorhersageregel abgeleitet um nachfolgend eine Echtzeitvorhersage der räumlichen Transformation von unbekannten intra-interventionellen 2D Bildern vorzunehmen. Zwei TMR Methoden wurden implementiert und mit einer quantitativen Simulation von 120 Experimenten validiert. Die Experimente basieren auf realistischen lateralen und ventralen IGRT Szenarien mit 15 unterschiedlichen, klinischen Computertomographie (CT) Datensätzen und synthetischen 2D Röntgenbildern (DRRs). Die implementierten TMR-Methoden sind TMR-PCR, welche Hauptkomponentenregression (PCR) verwendet, und TMR-KPCR, welche Kernel-PCR verwendet.

Die Ergebnisse zeigen dass TMR fähig ist die translatorischen Parameter ($\overline{\text{MSE}}$ 0.004-0.913 mm^2), welche perpendikular zur Projektionsrichtung stehen, und Rotationen in dieser Ebene ($\overline{\text{MSE}}$ 0.055-0.495 deg^2) mit hoher Genauigkeit vorherzusagen. Die Vorhersage der Tiefeninformation war erwartungsgemäß weniger genau ($\overline{\text{MSE}}$ 2.409-13.211 mm^2), da nur ein einziges Bild verwendet wurde. Die Maximalwerte des 95sten Registrierungsfehler (mTRE) Perzentils zeigen dass TMR unter Idealbedingungen eine sehr robuste Vorhersage liefert (1.156-2.556 mm), sogar bei hohen initialen mTREs. Ein erhöhter $\overline{mTRE}$ (0.194-1.59 vs. 0.531-4.184 mm) wurde bei feineren CT Datensatzauflösungen beobachtet. Mehr Details in den DRRs und die verwendeten nicht-robusten statistischen Methoden (anfällig für überhöhte Varianz und verrauschte Pixel) verringern die Generalisierbarkeit. Mehr Freiheitsgrade (DOF) der Transformation führen zu einer weniger verlässlichen Registrierung (3.01-16.15 mal höherer mittlerer $\overline{mTRE}$). Dies kann hauptsächlich auf die steigende Dimensionalität des Parameterraumes zurückgeführt werden und ist beherrschbar mit mehr Samples der Trainingsmenge und besseren Vorverarbeitungsschritten. Die Experimente vom Kopf/Hals-Bereich haben eine höhere Genauigkeit als die Prostataexperimente. Die lateralen und ventralen Experimente haben eine gleichwertige Performanz.

Die durchschnittlichen intra-interventionellen Registrierungsraten von 43.84 und 64.92 Hz sind beachtlich. TMR-PCR ist nicht in der Lage Nichtlinearitäten in den Transformationen abzubilden. TMR-KPCR mit einem polynomiellen Kernel vom Grad 3 erscheint als die Methode der Wahl. Die Mehrheit der 2D/3D Registrierungen in 60 Experimenten war erfolgreich (86.44-99.39%), wobei ein finaler mTRE kleiner 2 mm als erfolgreich definiert wurde. Die restlichen Experimente leiden deutlich unter den gesteigerten DOF (23.86-70,07%). Allerdings ist die Anzahl an 2D/3D Registrierungen mit einem höheren oder gleichen finalen mTRE als vor der Registrierung sehr gering (höchstens 0.1-0.31%).

TMR ermöglicht den Zugang zu einer großen Auswahl an Methoden und Algorithmen, die üblicherweise im Zusammenhang mit maschinellem Lernen und “Computer Vision” eingesetzt werden. Zusammenfassend sind die Ergebnisse der sehr einfachen TMR Konfiguration aussichtsreich für eine Verwendung im Umfeld der automatischen, echzeitbasierten, 2D/3D Registrierung und anderen Bereichen der IGMI.

Contents

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