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The R2D2 paradigm for ultra-fast high-dynamic range imaging in radio astronomy

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Mapping the radio sky with the new modern radio-interferometric (RI) arrays requires solving challenging inverse problems for the formation of high-resolution high-dynamic range images from large volumes of visibility data. A new generation of image reconstruction algorithms grounded in optimization theory have demonstrated remarkable capability for imaging precision, well beyond the capability offered by CLEAN. These range from advanced proximal algorithms propelled by handcrafted regularization operators, such as the SARA family [1, 2, 3, 4], to hybrid plug-and-play (PnP) algorithms propelled by learned regularization denoisers, such as AIRI [5]. While already capable of scaling to large image and data dimensions, these techniques are highly iterative, which still hinders their ability to handle the extreme data volumes expected from future instruments. To address this scalability challenge, a novel deep learning approach was recently proposed, dubbed "**R**esidual-to-**R**esidual **D**NN series for high-**D**ynamic range imaging" [6, 7]. **R2D2**'s reconstruction is formed as a series of residual images, iteratively estimated as outputs of DNNs taking the image estimate from the previous iteration and the associated data residual as inputs. R2D2 thus features a hybrid structure between a PnP algorithm and a learned version of the matching pursuit algorithm underpinning CLEAN.

We discuss two incarnations of the R2D2 paradigm. The first one uses the well-known U-Net architecture for its DNNs, and is simply referred to as R2D2. The second one uses a more advanced architecture dubbed R2D2-Net, obtained by unrolling the R2D2 algorithm itself. In reference to its nesting structure, we refer to the latter incarnation as "**R**ussian **D**oll **R2D2**", in short R3D3. The capability of R2D2 and R3D3 for joint precision and scalability is showcased in simulation across a variety of image and data settings. Firstly, both R2D2 and R3D3 are shown to deliver yet another step change in achievable resolution and dynamic range over the SARA family and AIRI. Secondly, R2D2 typically requires a bit more than 10 iterations to clean data residuals at dynamic ranges up to 10^5, while R3D3 achieves the same precision in less than half of that number of iterations thanks to the powerful unrolled architecture of its DNNs. The new R2D2 paradigm thus provides a significant acceleration over the SARA family, AIRI, and CLEAN, opening the door to ultra-fast high-resolution high-dynamic range RI image reconstruction. R2D2 and R3D3 are also demonstrated on real observations of the radio galaxy Cygnus A at S band, from the Very Large Array [8].

References

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